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EMPIRICAL EVALUATION OF THE MK 16 MOD 1 UBA BREATHE-DOWN PROCEDURE

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Guidance for using new helium-oxygen (He-O_2) decompression tables for the MK 16 MOD 1 underwater breathing apparatus (UBA) includes recommended performance of a predescent breathe-down procedure (BDP) to reduce descent-induced overshoot of diver-inspired oxygen partial pressure (PO_2). This report describes work completed at NEDU to test the efficacy of this procedure. Thirty-two MK 16 MOD 1 He-O_2 man-dives to 300 feet of seawater (fsw) were completed in the NEDU Ocean Simulation Facility: 16 with descent preceded by performance of the BDP, and 16 without BDP before descent. Diver-inspired PO_2 was measured with an O_2 fuel cell positioned in the base of the inhalation hose on the UBA, and with mass spectrometric analysis of a gas stream sampled from the same site. Peak PO_2 after descent at a mean rate of 60 fsw/min was not significantly different between BDP (1.92 ATA) and No-BDP (1.91 ATA) groups ($P = 0.81$). It is recommended that the BDP be removed from standard operating procedures for MK 16 MOD 1 diving. Two DCS incidents in 12 dives completed with the 300 fsw/10min schedule from the MK 16 MOD 1 He-O_2 tables motivate a recommendation that a MK 16 MOD 1 He-O_2 diver who has not completed prior work up dives should use the decompression schedule for his actual or planned bottom time at the next tabulated dive depth deeper than his actual or planned dive depth if the latter is greater than 200 fsw.

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INTRODUCTION

BACKGROUND

The MK 16 MOD 1 underwater breathing apparatus (UBA) is a closed-circuit rebreather that maintains diver inspired oxygen partial pressure (PO_2) nearly constant at 1.30 atmospheres absolute (ATA) at depths greater than about 30 feet of seawater (fsw). During descent, compression of the UBA gas volume and addition of diluent gas and oxygen (O_2) drive the PO_2 in this UBA to values that exceed the 1.30 ATA set point. As the diver metabolizes the O_2 in the UBA, he/she breathes down this "PO_2 overshoot" within minutes after reaching bottom depth. However, because the magnitude of the PO_2 overshoot increases with dive depth and descent rate, PO_2 values high enough to cause concern about the occurrence of central nervous system (CNS) oxygen toxicity can be achieved during and immediately after descents from surface to depths in excess of about 200 fsw. A procedure intended to mitigate this concern aimed directly at reducing the magnitude of the PO_2 overshoot by breathing-down the UBA PO_2 to a value lower than the UBA surface PO_2 setting of 0.75 ATA immediately before descent is started. This predescent "breathe-down procedure" (BDP) was included in recommended MK 16 MOD 1 standard operating procedures for dives to depths of 250 fsw or deeper.[3]

More recent and comprehensive theoretical analyses indicate that the predescent BDP can in fact only insignificantly reduce descent-driven PO_2 overshoots in the MK 16 MOD 1. With empirical confirmation of this indication, the predescent BDP could be removed from MK 16 MOD 1 standard operating procedures.

PROGRAM OBJECTIVES

The objective of this study was to confirm theoretical indications that the predescent BDP can only insignificantly reduce peak PO_2 attained during descent in MK 16 MOD 1 helium-oxygen ($He\text{-}O_2$) dives. This objective was sought to establish a recommendation to remove the BDP from standard operating procedures for MK 16 MOD 1 dives.

METHODS

The overall approach was to monitor diver inspired PO_2 during MK 16 MOD 1 $He\text{-}O_2$ man-dives in the Navy Experimental Diving Unit (NEDU) Ocean Simulation Facility (OSF), and compare peak inspired PO_2 values during dives completed after the BDP had been performed to those attained in dives completed without performance of the BDP. Testing was started on 300 fsw dives, the deepest normally allowed with the MK 16 MOD 1, and those in which the breathe-down procedure should have greatest effect. Testing was to cease once the procedure was found be ineffective on these dives.

The number of dives was planned to allow declaration with 95% confidence and 80% power that the BDP is "effective" if it reduces peak PO_2 by 0.2 ATA or more. Statistical power calculations[6] indicate that, if the standard deviation of observed peak PO_2 values is also 0.2 ATA, 32 exposures are required for 80% probability of detecting an actual difference of this magnitude at 95 % confidence: 16 completed with the predescent BDP performed, and 16 without. Failure to detect such a difference in this number of exposures would then motivate the conclusion that the BDP is "ineffective."

A human use protocol (NEDU Protocol Number 03-06/32122) was prepared which provided detailed descriptions of the scientific and procedural aspects of the study. The NEDU Committee for the Protection of Human-Subjects (CPHS) reviewed and approved this protocol before the man-dives commenced. Military divers who had read and signed consent forms served as test divers in this investigation. All test divers met the physical qualification standards for diving, were within the U.S. Navy height/weight standard, and were familiar with operation and use of the MK 16 MOD 1 and its associated standard and emergency procedures.

Dives using the MK 16 MOD 1 UBA with 88% He/12% O_2 diluent gas were conducted in NEDU's OSF wet pot. The divers remained submerged and at rest throughout each dive profile; in a near horizontal position in cycle ergometer stands on the OSF platform during compression and time at bottom, and in a seated upright position with legs outstretched in the ergometer stands during decompression. Water temperature was controlled at 80 $\pm$ 2°F (26.7 $\pm$ 1.1°C). Divers wore full wet suits to retain body heat. A hot water hose was available to provide supplemental heat, as needed. The oxygen, nitrogen, helium, and carbon dioxide concentrations in each rig were monitored by Medical Deck as described in Section 2.2. The Diving Watch Supervisor (DWS) controlled the dives and monitored all diving via video cameras in the wet pot. A hydrophone was placed in the wet pot for communication with all test divers.

The divers used the MK 16 MOD 1 UBA with the KMS 48 full face mask (FFM) with communications. Two additional MK 16 MOD 1 UBAs accompanied the divers as emergency breathing systems (EBS). Emergency gas supply (EGS) was also available to each diver via a second-stage regulator (hookah) at the diver's station on the OSF wet pot platform. Emergency gas was supplied to these hookahs at 135 psi over bottom pressure via a facility regulator and a manifold in the wet pot overhead.

The EGS gases (Table 1) were specified to minimize the number of EGS gas switches required during ascent, and to allow the divers breathing those gases to be decompressed on the same schedule as that of other divers remaining on the MK 16 MOD 1 or EBS.

Table 1.
EGS Gas Schedule

- Breathe 12% O_2-in-He EGS mix through decompression to 130 fsw;
- Switch to 50% O_2-in-He on reaching 130 fsw and breathe through decompression to 50 fsw;
- Switch to 100% O_2-in-He on reaching 50 fsw and breathe through remaining decompression to surface.

The EGS gas O_2 fractions and corresponding inspired PO_2 values at various depths are shown in Table 2.

Table 2.
EGS Gas O_2 Fractions and Partial Pressures

Depth, fsw	EGS O_2 Fraction, %	Dry gas PO_2, atm, of indicated mix at indicated depth
300	12.0	1.208
131	12.0	0.595
130	50.0	2.465
51	50.0	1.271
50	100.0	2.512
20		1.605
SURFACE	100.0	1.000

The MK 16 MOD 1 UBAs in this study were all fitted with the upgrade Teledyne R10-DN oxygen sensors.[1] Each UBA was also fitted with a gas sampling block in the inhalation hose at its juncture with the backpack. This sampling block contained a Teledyne R10-DS O_2 fuel cell, a YSI thermistor, and a gas sampling port, with appropriate connections via an umbilical to instruments on the Medical Deck for monitoring diver inspired gas composition and temperature.

Each MK 16 MOD 1 was calibrated using standard procedures during setup prior to each day's diving.

DIVE PROCEDURES

The wet pot water level was set so that each diver's mid-axillary line was 2–3 feet below the surface of the water when the diver was in position on the platform.

Tenders assisted the divers in dressing for each dive and in entering the wet pot, but tenders exited the chamber before hatch closure and compression. During the dive, divers acted as tenders for each other, while surface tenders remained in the immediate area of the OSF so that, in an emergency, they could quickly be compressed to depth and could serve as in-chamber tenders if the DWS required them to do so.

Provisions were in place to switch a diver to a backup MK 16 MOD 1 (EBS) or to the EGS if the diver's inspired PO_2 reached a level

- greater than 1.45 ATA and less than or equal to 2.0 ATA for 15 consecutive minutes, or
- greater than 2.0 ATA and less than or equal to 2.4 ATA for 5 consecutive minutes, or
- greater than 2.4 ATA at any time.

Failure of a diver's MK16 MOD 1 UBA to deliver inspired PO_2 in excess of 0.4 atmosphere (atm) at any time during a dive was also cause to switch that diver to an EBS, or to an EGS if an EBS was unavailable.

Preparation and Compression

The dive team for each dive consisted of 4 divers, designated RED, GREEN, YELLOW and BLUE, respectively. RED and GREEN divers and YELLOW and BLUE divers were buddy-paired. The divers in one diver pair were selected to perform the predescent BDP by coin toss during the predive brief.

When directed by the DWS, divers dressed in wet suits and emergency recovery harnesses with the assistance of the OSF duty section trunk tenders. Divers then donned their UBAs and completed a predive check outside Alpha chamber, while the DWS ensured that each test diver was appropriately dressed and had a properly functioning MK 16 MOD 1.

The test divers then proceeded in order — RED, GREEN, YELLOW, and BLUE — into the chamber and to the transfer trunk, where a tender completed umbilical connections for gas sampling, inspired gas temperature monitoring, and communications. After these connections were completed on each diver, he donned his mask, switched the rig to "ON GAS," completed three open-circuit breaths to purge N_2 from the rig, and completed a communications check. He then entered the water and proceeded to his station on the OSF platform, where he assumed a near-horizontal position in a cycle ergometer stand. He remained in this position in the stand harnesses until dive time on bottom elapsed, unless he temporarily assumed a standing position to perform the BDP, as noted two paragraphs below. After all divers were in position, the tenders exited the chamber, and the Charlie/Bravo and Charlie/Delta hatches were closed.

With divers at their stations, a 3-minute monitoring period was allowed for divers and Medical Deck personnel to verify that all diver-inspired PO_2 values were near the 0.75 ATA set point, and for each diver to receive a steady green status indication on the primary display of his MK 16 MOD 1 UBA. During this period the open circuit gas supply was switched from air to bottom mix (12%/88% O_2-in-He; see Table 1).

After completing the 3-minute UBA stabilization period and receiving OKs from all test divers, the DWS directed the two divers selected to perform the BDP to do so. Divers performed the BDP either while they were completely water-immersed and in their ergometer stands, or while their heads were above water after the divers had temporarily stood at their stations on the OSF platform.

The procedure, which consisted of repeated inhalation from the rig followed by exhalation into the surrounding water or air, was performed as follows:

1. Diver inhaled to near-maximum lung volume from the rig and held breath.
2. While in end-inspiratory breath-hold, diver switched his barrel valve on his MK 16 gas switchblock to "OFF GAS."
3. Diver exhaled maximally into his mask while venting the exhaled gas into the surrounding water or air, then held his breath.
4. Diver switched his MK 16 gas switchblock back to "ON GAS."
5. Diver repeated steps 1 through 4 two additional times.
6. Diver resumed normal breathing, beginning with inspiration.

Immediately after the divers selected to perform the BDP completed it, the complex was compressed on air to 297 fsw at a target rate of 60 fsw/min. Divers gave OKs throughout the compression. If a compression rate of 60 $\pm$ 5 fsw could not be achieved and maintained because an ear or sinus squeeze or any other emergency occurred, a dive was to be aborted and the complex returned directly to the surface. Such an abort was not necessary during any of the dives.

The 297 fsw chamber bottom pressure plus the 3 fsw water pressure at diver average mid-chest level while in the ergometer harnesses was equal to the intended dive depth pressure of 300 fsw. Depth was monitored with the Charlie chamber Digigauge, which was calibrated and zeroed before each day's diving. The Digigauge was backed up by a Bourdon gauge, which was also zeroed before each day's diving, on the Charlie chamber manual operation panel (MOP).

At Depth

Divers remained under direction of the DWS at depth and remained at rest in the harnesses of the ergometer stands. The DWS directed each of the divers, in turn, to provide PO_2 readings from their UBA secondary displays to Medical Deck personnel, who recorded these readings. Medical Deck personnel advised the DWS when their instrumentation had obtained satisfactory measures of post-compression diver-inspired PO_2 for all divers. Divers were then instructed to prepare for decompression by assuming a seated upright position with legs outstretched in the ergometer stands. Bottom time did not exceed 15 min during any dives completed in this study.

Decompression

Decompressions were conducted according to the appropriate schedule from the MK 16 MOD 1 $He\text{-}O_2$ decompression tables.[1,3] The chamber pressure at each decompression stop was offset to that corresponding to a depth 3 fsw shallower than the stop depth indicated in the schedule to correct for diver mid-chest water depth in the chamber. Divers remained resting and in the seated upright position in the ergometer stands, aided by weights as necessary, throughout decompression. Decompression between stops proceeded at a rate as close to 30 fsw/min as possible. The emergency gas mixtures were shifted at the depths outlined in Tables 1 and 2. After each shift, the divers were instructed to complete a 1-minute purge of their hookahs to bleed previous EGS gas from the feed lines.

Divers were instructed to refrain from manually adding oxygen to the UBA unless instructed to do so by the Medical Deck, the DWO, or the DWS; or if their secondary display showed a PO_2 less than 0.4 ATA. Divers were instructed to notify the DWS in the event of such an addition. If the Medical Deck observed a rig PO_2 less than 1.1 ATA, either on the mass spectrometer or the R10-DS fuel cell at any time after 2 min into the second decompression stop of a dive, the Medical Deck recommended DWS to advise the affected diver to add O_2 via his/her O_2 bypass button or switch to EGS.

Surfacing

When the OSF reached the surface, the DWS directed test divers to stand up, proceed to the trunk, turn their switch-blocks to the "OFF GAS" position to close the MK 16 MOD 1 breathing loops, remove their full face masks, and breathe chamber air.

The test divers then exited the OSF through Alpha chamber in an order reversed from that of their entry (BLUE, YELLOW, GREEN, then RED). They remained in the immediate vicinity of the OSF for 10 minutes, after which the DWS cleared them to leave the OSF area.

Test divers remained at NEDU for the ensuing 2 hr, after which the Dive Watch Medical Officer (DWMO) interviewed them for clearance to leave NEDU. Divers were instructed not to fly, dive, or expose themselves to hyperbaric pressure (except as test divers under this protocol) for 48 hours after their last surfacing.

Instrumentation

A computerized data acquisition system was used on the OSF Medical Deck to monitor diver depth, inspired gas composition, and temperature, and automatically record these data in ASCII text file format in real-time throughout every dive.

DIVER INSPIRED GAS ANALYSIS

The objective of present work was to ascertain the influence of the predescent Breathe-Down Procedure on diver inspired PO_2 in the MK 16 MOD 1 UBA. To this end, two independent methods were used to monitor diver-inspired PO_2 throughout each dive.

MASS SPECTROMETRIC MONITORING

Oxygen, nitrogen, helium, and carbon dioxide concentrations in a gas stream sampled from the gas sample block at the base of each diver's MK 16 MOD 1 inhalation hose were monitored using methods described in Appendix G of NEDU TR 02-10.[1]

OXYGEN FUEL CELL MONITORING

Diver inspired O_2 partial pressures were also monitored using a Teledyne R10-DS O_2 fuel cell positioned in the gas sample block at the base of the inhalation hose on each MK 16 MOD 1.

Data from each diver's O_2 fuel cell was recorded in the real-time record as PO_2 in atmospheres, which was obtained by conversion of measured fuel cell voltage output. This conversion from measured voltage, V, to recorded PO_2, $P^{R}_{O_2}$, was performed in real-time based on a linear operational calibration line for each fuel cell:

$$V = \beta_0 + \beta_1 P^{R}_{O_2}. \tag{1}$$

The slope β_1 and intercept β_0 of this line were determined from measured voltage outputs of the fuel cell flushed at sea level with air (PO_2 = 0.21 atm) and 100% O_2 (PO_2 = 1.00 atm) during setup on the morning of each dive day:

$$\beta_1 = \frac{V_{100\%\,O_2} - V_{\mathrm{Air}}}{1.00 - 0.21}, \tag{2}$$

and

$$\beta_0 = V_{\mathrm{Air}} - (\beta_1 * 0.21), \tag{3}$$

where $V_{100\%\,O_2}$ is the output of the cell when flushed with 100% O_2, and V_{Air} is the output of the air-flushed cell.

The descent-driven PO_2 overshoot in the MK 16 occurs during and immediately after compression, when the rapidly changing pressure and associated changes in gas sample flow to the mass spectrometer make corrections of mass spectrometric data for latency and response time unreliable. Diver-inspired PO_2 during this period was consequently taken from information recorded from each diver's fuel cell. The accuracy of this information was improved by post run correction of recorded fuel cell PO_2 values for nonlinearities in fuel cell output versus PO_2.

Recorded fuel cell PO_2 values were corrected using fuel cell voltage outputs measured in the laboratory before and after the dive series. These measurements were made at a series of actual PO_2 values from 0.21 to 2.1 atm as each cell was compressed in air. Only small degradations in fuel cell performance, manifest as slight increases in curvature of the voltage output versus PO_2 curve for each cell, were found to have occurred throughout the dive series. These degradations were neglected and the preseries data were combined with the postseries data for each cell. The combined data for each cell were then fitted by a quadratic equation in actual PO_2 ($P_{O_2}^A$);

$$V = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2; \qquad (4)$$

using linear least-squares regression to obtain a laboratory calibration curve for each cell. Preseries, postseries, and fitted laboratory calibration lines for each of the four fuel cells used in this study are given in Appendix A, along with the values of the coefficients of Eq. (4) fitted to the combined data for each cell.

The corrected fuel cell PO_2, $P_{O_2}^A$, for each recorded value in the real-time record was obtained by finding the root of Eq. (4) at the V for the recorded $P_{O_2}^R$ determined from Eq. (1):

$$P_{O_2}^A = \frac{-\beta_1^L + \sqrt{\left(\beta_1^L\right)^2 - 4\beta_2^L\left(\beta_0^L - V\right)}}{2 \cdot \beta_2^L}. \qquad (5)$$

The slope β_1 and intercept β_0 for solution of Eq. (1) were determined from Eqs. (2) and (3), with $V_{100\%\,O_2}$ and V_{Air} determined from Eq. (4) with $P_{O_2}^A = 1.0$ and $P_{O_2}^A = 0.21$, respectively. The process is schematized in Figure 1.

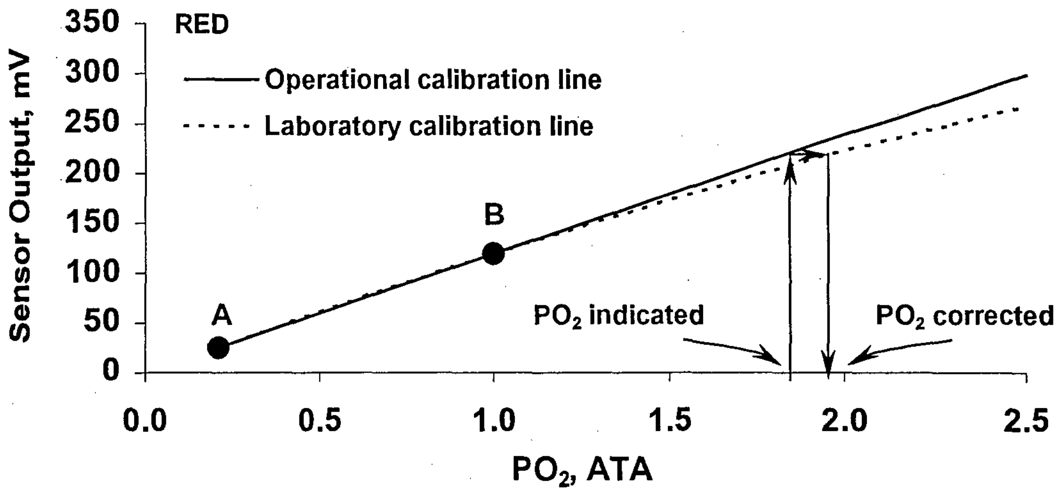

Figure 1. Correction of R10-DS oxygen fuel cell PO_2 readings for nonlinearity in response versus PO_2. The laboratory calibration line was obtained from a quadratic equation fitted by least squares regression to measured fuel cell output at PO_2 from 0.21 to 2.1 ATA. The operational calibration line is drawn through the sea level air (PO_2 = 0.21 ATA) and 100% O_2 (PO_2 = 1.0 ATA) points on the laboratory calibration line at the indicated points **A** and **B**, respectively; *i.e.*, the response of each fuel cell was assumed linear for operational purposes. Indicated PO_2 in raw fuel cell data was inverted through the operational calibration line to the laboratory calibration line to obtain the corrected PO_2. Note that corrected PO_2 values are greater than indicated values at $PO_2 > 1.0$ ATA, and less than indicated values at PO_2 between 0.21 and 1.0 ATA.

RESULTS

Thirty-two test dives were successfully completed; 16 were preceded by performance of the predescent BDP and 16 were not. All dives were completed without an abort, or any incident that required diver resort to EBS or EGS. Data sufficient to evaluate the efficacy of the BDP were obtained from 28 of these dives; 16 that had been preceded by performance of the BDP and 12 that had not.

Overall results are summarized in Table 3. Graphical renditions of the measured dive depth and diver inspired PO_2 for each dive are given in Appendix C. The profile for each dive is identified with a format that indicates the date of the dive (YYMMDD) and the diver color identifier followed by a letter "a" or "b" to indicate whether the dive was the first or second, respectively, on the indicated date.

Table 3.

Results Summary: MK 16 MOD 1 UBA Predescent BDP Evaluation

Profile	Dive Depth (fsw)	DSCNT RATE (fsw/min)	BOTTOM Time (min)	Total Dive Time (min)	Predescent PO_2 minimum (ATA)	Max PO_2 (R10-DS) (ATA)	BDP (Y/N)
030312BLUb	304.5	64.0	9.3	38.4	0.693	1.967	N
030312GRNa	303.8	66.4	12.3	104.3	0.663	1.813	N
030312GRNb	304.5	64.0	9.3	38.4	0.383	1.808	Y
030312REDa	303.9	66.4	12.4	104.3	0.738	1.670	N
030312REDb	304.5	64.0	9.4	38.4	0.496	2.047	Y
030312YELb	304.6	64.0	9.3	38.3	0.735	1.782	N
030313BLUa	300.1	65.8	9.7	38.3	0.362	1.996	Y
030313BLUb	301.7	58.9	9.6	38.1	0.713	1.876	N
030313GRNa	300.0	66.2	9.7	38.3	0.691	1.970	N
030313GRNb	301.7	55.1	9.5	38.1	0.399	1.881	Y
030313REDa	300.0	65.8	9.7	38.3	0.711	1.676	N
030313REDb*	301.7	55.2	9.6	38.1	0.466	1.975	Y
030313YELa*	300.0	65.8	9.7	38.3	0.288	1.773	Y
030313YELb	301.7	58.9	9.6	38.1	0.691	1.952	N
030318BLUa	301.4	54.3	10.9	102.9	0.435	1.948	Y
030318BLUb	303.4	56.5	5.3	47.1	0.725	2.066	N
030318GRNa	301.4	54.1	10.9	102.8	0.647	1.904	N
030318GRNb	303.4	56.6	5.3	47.2	0.349	1.776	Y
030318REDa	301.4	54.8	10.9	102.8	0.747	1.926	N
030318REDb	303.4	56.6	5.3	47.2	0.407	2.092	Y
030318YELa	301.5	54.1	10.9	102.9	0.353	1.767	Y
030318YELb	303.4	56.5	5.3	47.2	0.643	1.946	N
030320BLUa	301.4	59.0	9.8	101.8	0.679	2.073	N
030320BLUb	301.2	56.6	9.9	101.6	0.565	1.985	Y
030320GRNb	301.3	59.8	10.0	101.6	0.705	1.913	N
030320REDb	301.3	59.9	9.9	101.6	0.784	2.057	N
030320YELa	301.4	59.0	9.7	101.7	0.641	2.006	N
030320YELb	301.3	56.2	9.9	101.6	0.403	2.034	Y

* DCS

EFFICACY OF THE BREATHE-DOWN PROCEDURE

The efficacy of the BDP was ultimately assessed in terms of the peak diver inspired PO_2 reached during and after descent, but any effect of this procedure on this feature of the dive profile could not be expected unless the BDP had first reduced the rig PO_2 at the start of descent. As illustrated in Figures 2 and 3, measured rig PO_2 profiles allowed confirmation that such predescent PO_2 reductions were in fact achieved when the BDP was performed.

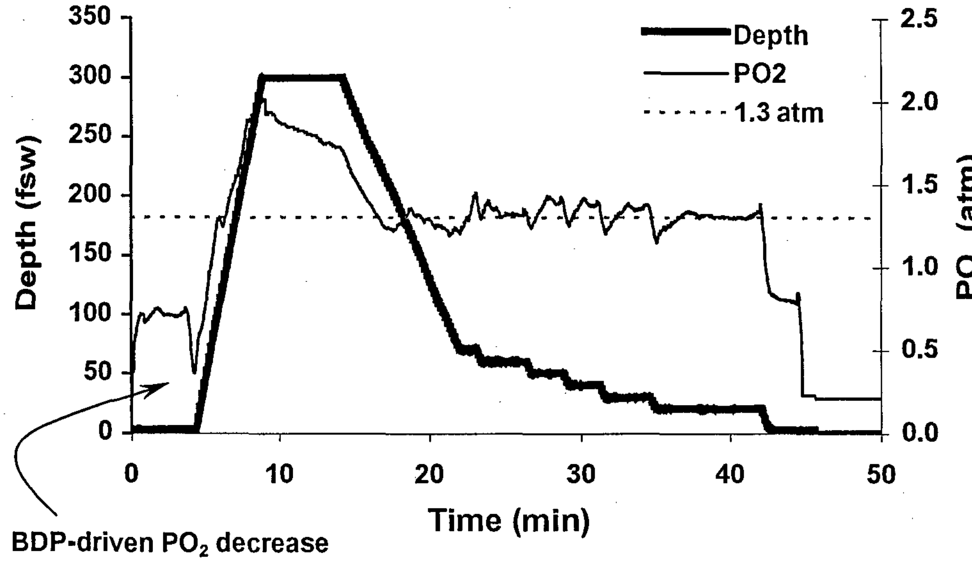

Figure 2. Pressure and inspired PO_2 profile for dive in which descent was preceded by performance of the BDP. Note the BDP-driven PO_2 decrease immediately before descent start. (profile 0303BLUa)

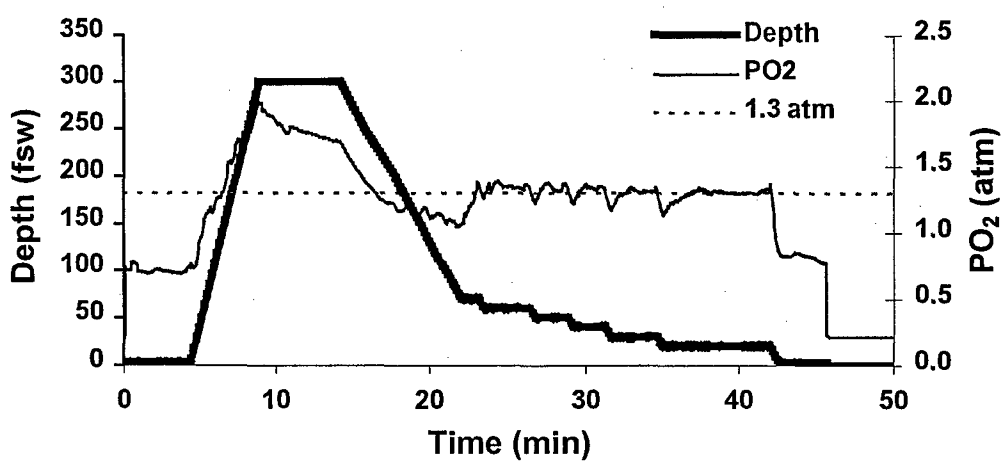

Figure 3. Pressure and inspired PO_2 profile for dive in which descent was not preceded by performance of the BDP. Note the absence of a conspicuous PO_2 decrease immediately before descent start. (profile 0303GRNa)

Immediate predescent diver inspired PO_2 values are compiled separately for all divers in the BDP and No-BDP groups in Table 4. Performance of the BDP reduced predescent diver inspired PO_2 from an average of 0.70 ATA in the No-BDP divers to an average of 0.41 ATA in the BDP divers; a reduction of about 0.3 ATA.

Table 4.
Effect of the BDP On Diver Inspired PO_2 Immediately before Descent

	Immediate Predescent PO_2 (ATA)	
	NO-BDP	YES-BDP
	0.693	0.383
	0.663	0.496
	0.738	0.362
	0.735	0.399
	0.713	0.466
	0.691	0.288
	0.711	0.435
	0.691	0.349
	0.725	0.407
	0.647	0.353
	0.747	0.565
	0.643	0.403
	0.679	
	0.705	
	0.784	
	0.641	
mean	0.700	0.409
S.D.	0.040	0.074

P = 0.0000000015

The reduction of immediate predescent PO_2 achieved by the BDP did not translate into a reduced peak inspired PO_2 immediately after subsequent descent. Peak diver-inspired PO_2 values are compiled separately for the BDP and No-BDP groups in Table 5. The average peak-inspired PO_2 in the No-BDP group (1.91 ATA) did not differ significantly from that in the BDP group (1.92 ATA): P = 0.81. Moreover, the standard deviation of the measured peak PO_2 was about 0.12 ATA in both groups. From this figure, we estimate that with 12 divers in one group and 16 in the other, our probability of finding any real peak PO_2 difference greater than 0.13 ATA at P = 0.05 between the two groups was greater than 80%.[6] We are consequently confident in accepting the result that the BDP fails to provide any useful reduction of descent-driven inspired PO_2 overshoots in the MK 16 MOD 1 UBA.

Table 5.
Effect of the Predescent BDP On Maximum Diver Inspired PO_2 Attained during 60 fsw/min MK 16 MOD1 UBA Descents to 300 fsw

	Max PO_2 (ATA), R10-DS	
	NO-BDP	YES-BDP
	1.967	1.808
	1.813	2.047
	1.670	1.996
	1.782	1.881
	1.876	1.975
	1.970	1.773
	1.676	1.948
	1.952	1.776
	2.066	2.092
	1.904	1.767
	1.926	1.985
	1.946	2.034
	2.073	
	1.913	
	2.057	
	2.006	
mean	1.912	1.924
S.D.	0.124	0.118
	P =	0.810

DCS OUTCOMES

Two cases of DCS occurred in this series of 32 man-dives. Both cases occurred after dives that had been completed using the 300 fsw/10 min schedule in the 1.3 ATA PO_2-in-He Decompression Tables for the MK 16 MOD 1 UBA. Complete descriptions of these cases are given in Appendix B.

DISCUSSION

BREATHE-DOWN PROCEDURE AND PO_2 OVERSHOOT MITIGATION

Descent-driven increases in the PO_2 of breathing gases delivered to divers on closed-circuit UBAs have long been recognized.[5] These PO_2 overshoots became a major concern when closed-circuit UBAs were designed to deliver breathing gases with nominal PO_2 near the diver threshold for developing CNS O_2 toxicity. Developers of decompression tables for the Royal Navy Clearance Divers Breathing Apparatus (CDBA), a UBA similar to the U.S. Navy MK 16 MOD 1, created and successfully tested a predescent UBA BDP that reportedly mitigates the PO_2 overshoot problem in the CDBA.[4] News of this development reached NEDU through informal channels during the course of MK 16 MOD 1 He-O_2 decompression table development. Preliminary theoretical results supported the notion that such a procedure would also reduce descent-driven PO_2 overshoots in the MK 16 MOD 1. An adaptation of the procedure was consequently incorporated into guidance for use of the final MK 16 MOD 1 He-O_2 tables with dives to depths of 250 fsw or deeper.[3] However, incorporation of O_2 sensors with faster response times into the MK 16 MOD 1, and concern that the previously neglected effects of O_2 add valve opening during descent should also be considered, motivated re-examination of the conclusion that the predescent breathe-down procedure written for the MK 16 MOD 1 must reduce descent-driven PO_2 overshoots in this UBA.

The MK 16 MOD 1 PO_2 overshoot problem was theoretically examined in Appendix B of NEDU TR 02-10.[1] The present report updates those analyses to include the effects of O_2 add valve opening under the influences of changing UBA PO_2 set point and responses of the O_2 sensors to changes in UBA PO_2 during descent. We retain the equation numbers from Appendix B of reference 1 for ready reference, and add a ".u" suffix to each as we update them. Our update follows from the addition of only a single term to the mass balance equation for the gas content of the UBA circuit during a dive. Thus the original Eq. (B.2) becomes

$$\frac{dN_C}{dt} = \frac{dN_D}{dt} + \frac{dN_A}{dt} - \frac{dN_{met}}{dt} - \frac{dN_{ex}}{dt}, \qquad \text{(B.2.u)}$$

where $\frac{dN_C}{dt}$ is the molar rate of change of overall circuit gas content (in units of moles per unit time), $\frac{dN_D}{dt}$ is the molar rate of diluent gas addition, $\frac{dN_{met}}{dt}$ is the net molar rate of change of circuit O_2 and CO_2 contents from diver metabolism, $\frac{dN_{ex}}{dt}$ is the molar rate of gas venting from the rig via exhaust, and $\frac{dN_A}{dt}$ is the new term equal to the molar rate of O_2 addition through the O_2 add valve. Following the derivation in NEDU TR 02-10, but with this new additional term, we update what was originally Eq. (B.13) for the instantaneous rate of change of the circuit O_2 contents:

$$\frac{dn_{O_2}}{dt} = \left(\frac{X_{O_2} V_C}{RT_C}\right)\left(\frac{dP_C}{dt}\right) + \frac{P^o\left(X_{O_2} - 1\right)}{RT^o}\left\{V^o_{O_2} - V^o_A\right\}, \qquad \text{(B.13.u)}$$

where P_C is the circuit gas pressure assumed always equal to the ambient hydrostatic pressure; V_C is the circuit volume consisting of rig volume *per se* plus diver pulmonary vital capacity; R is the gas constant; T_C is the circuit gas temperature; P^o and T^o are the standard pressure and temperature, respectively; X_{O_2} is the O_2 fraction of the diluent gas; $V^o_{O_2}$ is the diver standard O_2 consumption rate; and V^o_A is the standard O_2 flow rate of the open O_2 add valve. In turn, the original Eq. (B.14) of Appendix B, which gives the instantaneous rate of change of circuit PO_2, becomes:

$$\begin{aligned} \frac{dP_{O_2}}{dt} &= \frac{RT_C}{V_C}\left(\frac{dn_{O_2}}{dt}\right) \\ &= X_{O_2}\left(\frac{dP_C}{dt}\right) + \frac{T_C P^o\left(X_{O_2} - 1\right)}{T^o V_C}\left\{V^o_{O_2} - V^o_A\right\} \end{aligned} \qquad \text{(B.14.u)}$$

Equations. (B.13.u) and (B.14.u) are readily used to evaluate the magnitude and duration of PO_2 overshoots during various hypothetical descents as they are affected by O_2 add valve opening under the influence of simulated responses of the O_2 sensors to changes in simulated UBA PO_2. Response of the O_2 sensor is simulated by first assuming that it varies with prevailing UBA PO_2 as a simple single-exponential function of time with time constant τ_S. After approximating the UBA PO_2 profile as a series of consecutive straight line segments of duration dt, the sensor PO_2 at the end of each segment, SP_{O_2}, is given by

$$SP_{O_2} = P_{O_2} + \left(SP^o_{O_s} - P_{O_2}\right)\cdot e^{-dt/\tau_S} + k_{O_2}\left[dt + \tau_S \cdot \left(e^{-dt/\tau_S} - 1\right)\right], \qquad (6)$$

where P_{O_2} is the UBA PO_2 at the end of the segment; $SP^o_{O_s}$ and $P^o_{O_2}$ are the sensor PO_2 and UBA PO_2, respectively, at the beginning of the segment; and

$$k_{O_2} = \frac{\left(P_{O_2} - P^o_{O_2}\right)}{dt}. \qquad (7)$$

The sensor PO_2 profile, which drives the simulated opening and closing of the O_2 add valve, is computed by numerically integrating Eqs. (B.13.u) and (B.14.u) with sufficiently small dt from the start of descent at $t = 0$, while solving Eq. (6) at each step.

When the simulated sensor PO_2 is greater than or equal to the prevailing PO_2 set point of the rig, the O_2 add valve is closed, $V^o_A = 0$, and Eqs. (B.13.u) and (B.14.u) reduce to the original Eqs. (B.13) and (B.14). However, when the sensor PO_2 is less than the prevailing rig PO_2 set point, the O_2 add valve is open, and $\dot{V}_A^o > 0$ (≈5 L(STP)/min). If such O_2 add valve opening occurs during descent, the UBA PO_2 increases faster than under the influence of diluent addition alone. The time course of UBA PO_2 as influenced by diluent addition and O_2 add valve opening with changing rig PO_2 set point during descent was schematized in Figure 21 of NEDU TR 02-10, which is redrawn here in Figure 4.

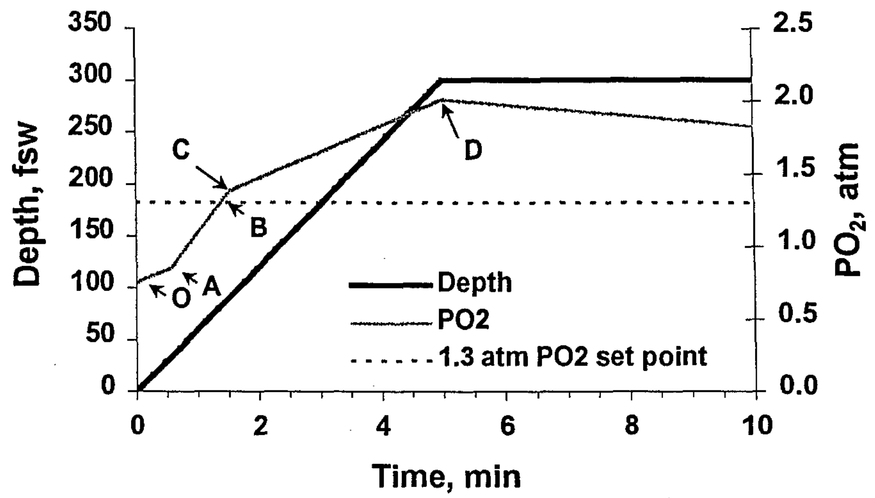

Figure 4. Diver-inspired PO_2 in MK 16 MOD 1 during hypothetical descent to 300 fsw at 60 fsw/min. UBA PO_2 at start descent was assumed to be 0.75 atm, and UBA O_2 sensors were assumed to have a 20-sec, 0–90% response time (typical for original equipment R10-DV sensors). Gas in the UBA and diver's lungs was assumed to be completely mixed throughout the simulation. When the 33-fsw PO_2 set point transition depth is attained at point A, the O_2 add valve opens; it closes at point C. Segments OA and CD have the same slope. The slope of segment AB exceeds that of segments OA and CD, an indication that rig PO_2 increases faster during the AB period than in the other periods, when only diluent is being added to maintain volume.

Figure 4 differs from its counterpart in NEDU TR 02-10 in that the illustrated PO_2-time curve extends to a computed peak PO_2 on arrival at 300 fsw (point D). Figure 5 illustrates the theoretical influences of different O_2 sensors and the BDP on this peak inspired PO_2 in hypothetical MK 16 MOD 1 dives to 300 fsw.

Completion of the BDP before descent reduces the PO_2 at descent start. Peak PO_2 versus diver O_2 consumption curves for such cases are shown in panels B and C of Figure 5. Comparing curves across the three panels reveals clearly that the BDP; *i.e.*, starting descent with successively lower PO_2 values; substantially reduces peak PO_2 at given O_2 consumption rates only when diluent is the only gas added to maintain UBA volume during descent. Reduced PO_2 at descent start has little effect on subsequent peak PO_2 values when maintenance of UBA volume is augmented by 100% O_2 addition after O_2 add valve opening. This absence of effect is partly because the O_2 add valve is already open at the start of descent (point O in Figure 4) when prior performance of the BDP has reduced the PO_2 to a value below the 0.75 ATA UBA set point at the surface (See Fig. 2 and Table 4).

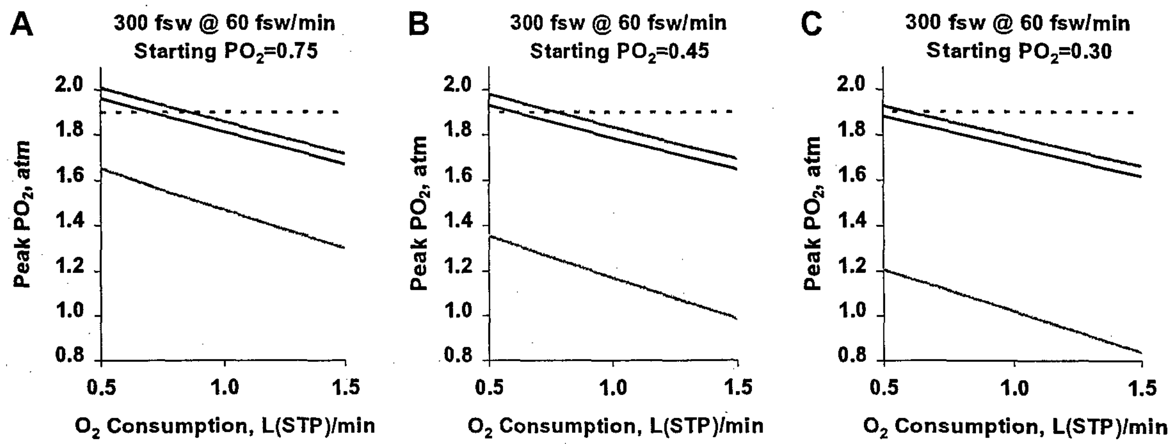

Figure 5. Peak PO_2 versus diver standard O_2 consumption for isovolumetric MK 16 MOD 1 descents to 300 fsw at 60 fsw/min with various PO_2 values at descent start. The *bottom* line in each panel is that obtained with UBA volume maintained by diluent addition only. The *middle* line in each panel is that obtained with UBA volume maintained by diluent addition plus O_2 addition as the O_2 add valve opens and closes under the influence of O_2 sensors with a 3-sec 0–90% response time (typical for upgrade R10-DN sensors). The *top* line in each panel is that obtained with UBA volume maintained by diluent addition plus O_2 addition as the O_2 add valve opens and closes under the influence of O_2 sensors with a 20-sec 0–90% response time (typical for original equipment R10-DV sensors). Curves for starting PO_2 of 0.75 atm in panel A correspond to descents performed without the BDP. Curves in panels B and C correspond to descents commenced after performance of the BDP has reduced the starting PO_2 to 0.45 and 0.30 atm, respectively. The horizontal dotted line in each panel indicates the 1.9 atm maximum allowed operational PO_2 in the MK 16 MOD 1 UBA.

Theoretical results in Figure 5 can be compared to those actually observed in our table development and validation dives,[1] which are summarized in Table 6. Theoretically predicted peak PO_2 values for very low diver O_2 consumption rates approach those observed in the NEDU dives, but remain lower than the observed values. Divers were in fact at rest with correspondingly low O_2 consumption rates during descent in the NEDU dives. Incomplete gas mixing in the real MK16 MOD 1 is the probable cause of any remaining discrepancies: Instantaneous and complete gas mixing was assumed in the theoretical calculations.

Table 6.
Measured Peak PO_2 in MK 16 MOD 1 He-O_2 NEDU Table Development and Validation Dives (NEDU TR 02-10)

Dive Depth (fsw)	# Dives	Peak PO_2 (atm)	Std. Deviation, Peak PO_2 (atm)
260	12	2.174	0.231
280	23	2.308	0.479
300	16	2.200	0.187

Other salient features of the theoretical results include:

- The faster response of the upgrade R10-DN O_2 sensors affords little reduction of the peak PO_2 compared to that attained with the slower R10-DV O_2 sensors;
- Oscillations in PO_2 after overshoot recovery do not arise from O_2 sensor response characteristics, but from gas mixing phenomena, which were not modeled in the present simulations.

In summary, theoretical results indicate that with accounting for O_2 addition from O_2 add valve opening, the BDP provides little reduction of the peak PO_2 attained during descent, and should not be required even for the deepest allowed MK 16 MOD 1 dives. Present experimental results confirm this indication, and imply that the currently-required predescent BDP for dives to depths greater than 200 fsw can be removed from the MK 16 MOD 1 standard operating procedures.

Present results are not in accord with those obtained with divers using the Royal Navy CDBA. Mottershaw, *et al.*,[4] report that breathing the CDBA counterlung down to as small a volume as possible prior to leaving surface reduces the magnitude of descent-driven PO_2 overshoots in this UBA on dives to 60 m or deeper. Use of 84% He/16% O_2 diluent gas in the CDBA compared to the 88% He/12% O_2 diluent used in the MK 16 MOD 1, and use of faster R10-DN O_2 sensors in the MK 16 MOD 1 may underlie this discrepancy.

DCS INCIDENCE AND THE WORK-UP PHENOMENON

Three schedules from the MK 16 MOD 1 He-O_2 decompression tables were used in this series. Four exposures were completed with the 310 fsw/10 min schedule, 16 with the 300 fsw/15 min schedule, and 12 with the 300 fsw/10 min schedule. The only 2 DCS cases in this series occurred on the latter schedule, giving an observed DCS incidence of 16.7%. The lower 95% binomial confidence limit of this incidence is 2.1%, an incidence indistinguishable from the 2.3% design DCS risk of the tables.[1] However, the lower limit of the observed incidence exceeds the 2.3% acceptable risk at a confidence of only slightly less than 95%. Given that the 300 fsw/10 min schedule was not tested in the MK 16 MOD 1 He-O_2 decompression table validation dives, the possibility that this schedule incurs an unacceptably high intrinsic DCS risk cannot be ruled out. We note that the 300 fsw/15 min schedule was dived 8 times, and the 300 fsw/ 20 min schedule was dived 7 times, without DCS incident in the validation dive series.[1] Six open-water MK 16 MOD 1 He-O_2 man-dives to depths ranging from 292 to 296 fsw with 7-min bottom times were also completed without incident using the 300 fsw/10 min schedule.[2]

We must also consider whether other factors might have made the present test divers more DCS-susceptible than the divers that completed the table development and validation dives, for which the overall DCS incidence was about 2.0%.[1] Failure of present divers to have completed work up dives before undertaking the present 300 fsw dives might have been such a factor. Work up or adaptation processes have been rather widely invoked to account for higher than anticipated DCS incidences in "fresh" divers and compressed air workers that have resumed diving or compressed air work after prolonged periods without hyperbaric exposure.[7]

For comparison to present experience, we examined the intensity of diving by individual divers in the MK 16 MOD 1 He-O_2 decompression table development and validation man dives to determine the extent to which the divers were "worked up" for each of their dives. Results are summarized graphically in Appendix D, where dives and counts of "prior" dives are based on individual dives in both single and repetitive dive profiles. Thus, a first dive preceding a second dive on the same day was counted as a prior dive to the second dive. Similarly, a first and second dive preceding a third dive on the same day were counted as two prior dives to the third dive. This counting scheme tended to inflate prior dive counts to values greater than one for repetitive dives and for dives undertaken on days after a diver had completed one or more repetitive dive profiles. It should be noted, however, that this consideration does not come into play for counts of divers that had completed zero dives before any given dive.

Overall, most divers that participated in the MK 16 MOD 1 He-O_2 decompression table development and validation dives had completed at least one other dive in the 10-day period preceding each dive, but many dives in both phases of the trials were completed without any prior dives even in the 15-day period before each dive. In particular, most Phase II divers that completed dives to depths in the 210-300 fsw range had not completed a prior dive in the preceding 5 days, or more than 2 dives in the preceding 15 days. Thus, the MK 16 MOD 1 He-O_2 decompression tables were validated using a substantial fraction of relatively fresh divers, and the tables should be applicable to such divers without modification. Nevertheless, the present 2/12 outcome using the 300 fsw/10 min schedule compels the conservative presumption that the fresh state of present divers contributed to the present DCS incidence in dives decompressed using the 300 fsw/10 min schedule, and hence, that some modest modification of MK 16 MOD 1 He-O_2 decompression schedules for divers that have not performed work-up dives should be made. In the absence of evidence motivating more widespread modifications, we limit our considerations of such modifications only to schedules for dives to depths greater than 200 fsw.

Thalmann addressed the accommodation of fresh divers in some detail during development of the 0.7 ATA PO_2-in-He decompression tables for the MK 16 MOD 0.[7] The final MK 16 MOD 0 He-O_2 decompression tables[7,8] were designed for divers that have not completed prior work-up dives, and were computed using the Exponential-Linear Real Time Algorithm (EL-RTA) with the HVAL21 set of Maximum Permissible Tissue Tensions (MPTTs). These tables had been preceded by another table set computed using the EL-RTA with the HVAL13 MPTT set. Schedules in the latter tables had shorter decompressions for longer deeper dives than the schedules in the final tables. DCS incidence remained acceptably low during man-testing of the these shorter schedules until testing was resumed after a three-month diving stand-down. An unacceptable DCS incidence using the EL(HVAL13)RTA schedules after this period motivated development of the more conservative final EL(HVAL21)RTA tables.[7]

Figure 6 illustrates the increases in decompression time that were incorporated into schedules for dives to depths greater than 200 fsw in the MK 16 MOD 0 tables to accommodate divers that have not completed prior work-up dives. The Linear-Exponential Multi-gas (LEM) probabilistic model[1] was used to compute the estimated DCS risks illustrated in Figure 7 of corresponding schedules in the EL(HVAL21)RTA and EL(HVAL13)RTA tables. Decompression times to accommodate fresh divers are substantially increased over those for worked-up divers for the longer dives at each depth, but are only little affected for the shorter dives. As a result, estimated DCS risks of schedules prescribed for fresh divers are noticeably reduced only for the longer dives at each depth. This reflects Thalmann's assertion that increased DCS susceptibility of fresh divers requires accommodation only in dives with bottom times greater than about 20 minutes.[7] Notably, however, even the largest stop time increases in the HVAL13 to HVAL21 accommodation result in final schedules that still incur substantial estimated DCS risks.

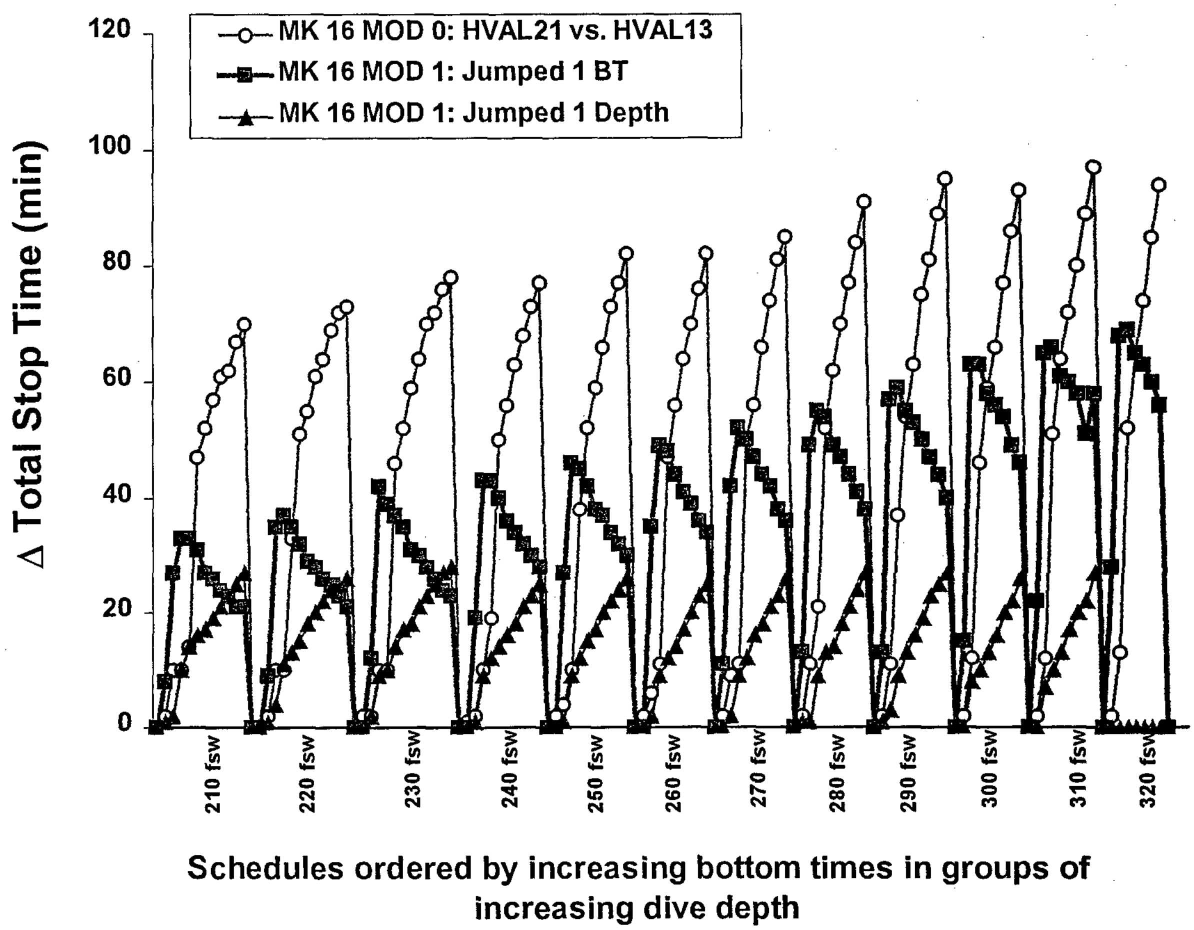

Figure 6. Increases in total stop time incorporated into 0.7 ATA PO_2-in-He MK 16 MOD 0 schedules for dives to depths in excess of 200 fsw to accommodate divers who have not completed recommended workup dives before MK 16 diving compared to corresponding increases in 1.3 ATA PO_2-in-He MK 16 MOD 1 schedules when similar accommodation is made in the latter either by adding 5 min to bottom time (Jumped 1 BT) or 10 fsw to dive depth (Jumped 1 Depth).

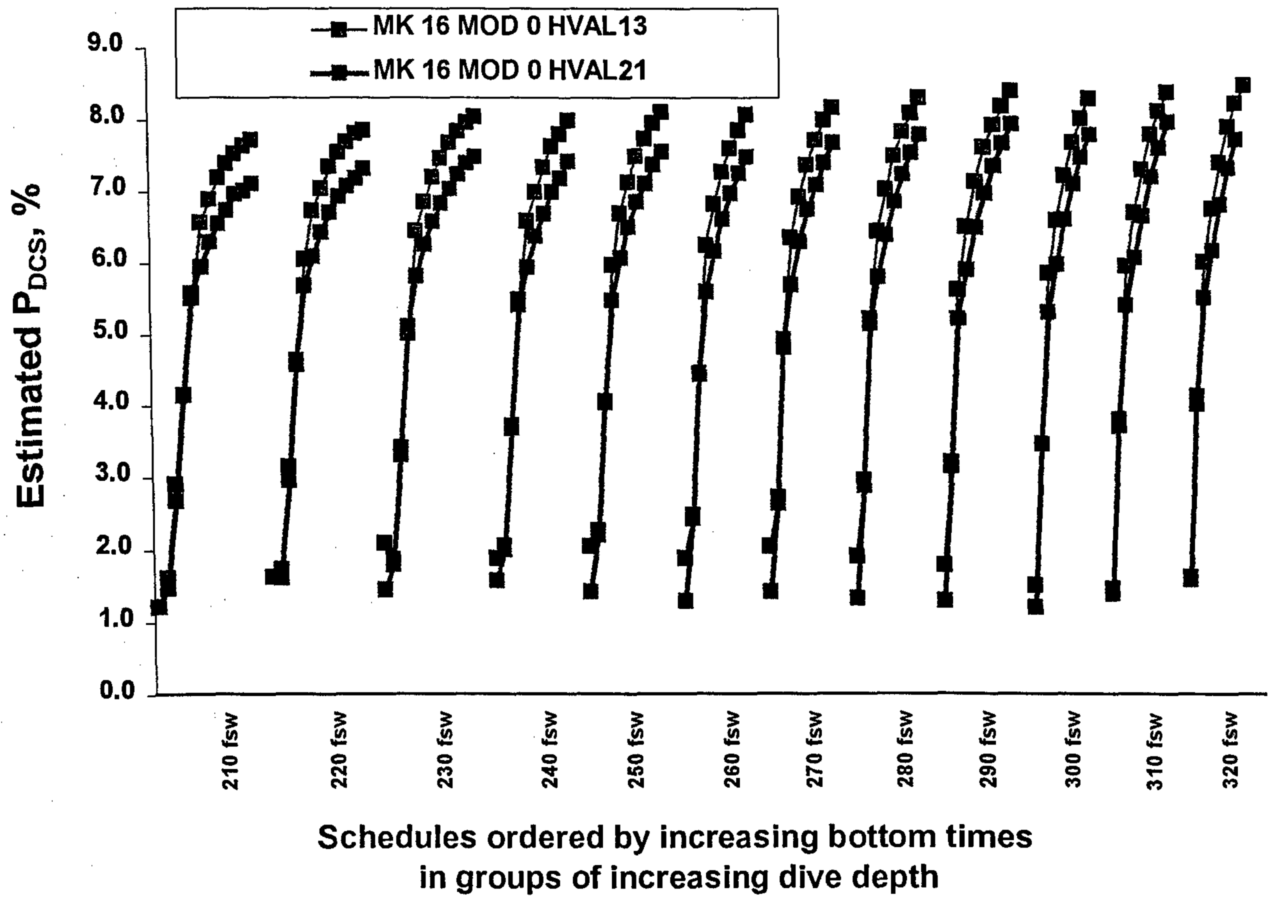

Figure 7. LEM-estimated DCS risks of schedules for dives to depths greater than 200 fsw in current 0.7 ATA PO_2-in-He MK 16 MOD 0 decompression tables [computed using the EL(HVAL21)RTA], and of schedules for the same dives in alternate 0.7 ATA PO_2-in-He tables developed for divers that have performed adequate work-up dives before MK 16 MOD 0 diving [computed using the EL(HVAL13)RTA].

Comparison of the EL(HVAL21)RTA and EL(HVAL13)RTA tables provides quantitative insights into how fresh divers might be accommodated in the MK 16 MOD 1 He-O_2 tables. Such accommodation can be made by recalculation of the tables, but only at high cost that is unwarranted by experience to date. Such accommodation is much more readily made through exercise of a simple rule based on the original tables themselves. Two alternatives are readily apparent: add 5 min to the planned or actual bottom time (jump to the next tabulated bottom time), or add 10 fsw to the planned or actual bottom depth (jump to the next tabulated dive depth) before entering the tables to determine the appropriate decompression schedule. Increases in total decompression stop time corresponding to each of these alternatives are illustrated in Figure 6, where they can be compared to the total stop time increases associated with the HVAL13 to HVAL21 accommodation. The increases for either alternative are less than those for the HVAL13 to HVAL21 accommodation at the longer bottom times at each dive depth. At the shorter bottom times, however, the increases incurred by jumping bottom time are greater than the corresponding increases in the HVAL13 to HVAL21 accommodation. The jump dive depth option incurs increases that are comparable to those incurred by the HVAL13 to HVAL21 accommodation in this region, and generally incurs total stop time penalties that increase with increasing dive bottom time, in accord with the notion that increased DCS susceptibility of fresh divers requires increasing accommodation for dives with longer bottom times.

Estimated DCS risks of schedules in the current MK 16 MOD 1 He-O_2 decompression tables, and of schedules modified according to each of the above two alternatives to accommodate fresh divers, are illustrated in Figure 8. The greatest reductions of estimated DCS risk are provided by addition of 5 minutes to the planned or actual bottom time before entering the tables, but these are bought with the largest increases in decompression time for all dives except those with the longest bottom times. The more modest accommodation warranted by present evidence favors the other alternative of adding 10 fsw to the planned or actual dive depth before entering the tables. Although the absolute estimated DCS risk reductions achieved by this alternative are only about 0.3%, the relative reductions are similar to the maximum relative risk reduction at each dive depth achieved by the HVAL13 to HVAL21 accommodation.

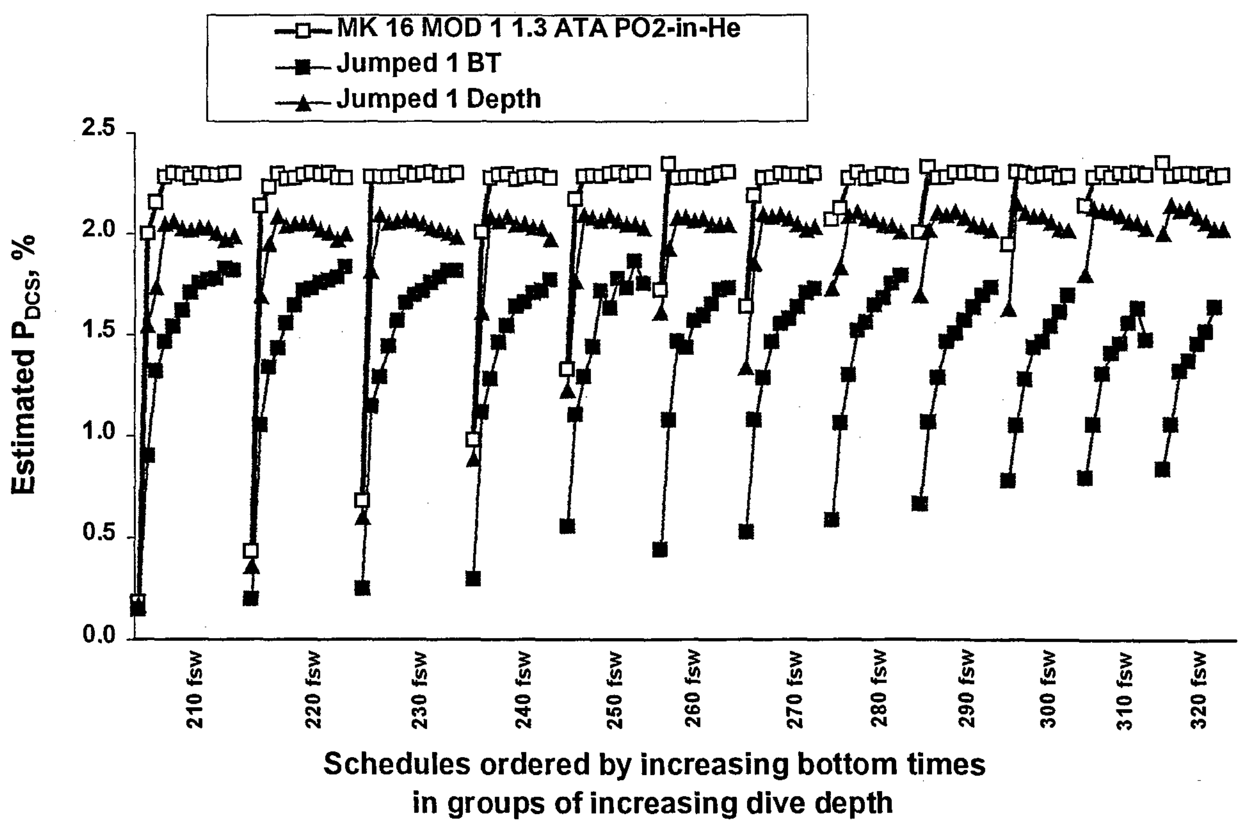

Figure 8. LEM-estimated DCS risks of MK 16 MOD 1 He-O_2 schedules as tabulated, and as dived under the two presently proposed alternatives to accommodate divers that have not completed work-up dives.

The problem remains to specify the work up period and the diving frequency, number of dives, and types of dives that are required during that period to work up a diver for any given dive. Although it is recognized that a diver probably accrues a continual decrease in DCS susceptibility up to some limiting level as diving experience accumulates, a binary distinction must be made here between a fresh diver and a worked up diver in the absence of more detailed information about the processes and kinetics involved. We can then define the worked up diver in terms of the individual diver histories that preceded most of the dives completed in the MK 16 MOD 1 He-O_2 decompression table validation dives. Referring to the individual dive intensities during these dives (Appendix D, Figures D.4 – D.6), few divers had completed more than two dives in the 10 days preceding any other dive (Figure D.5). In the context of the present MK 16 MOD 1 He-O_2 decompression tables, a diver who has completed more than two dives in the 10 days preceding any other dive can consequently be considered worked up for the latter dive. Considering that the effects of any work up dives probably wear off in from 5 to 10 days of diving inactivity, this specification is made more prudently conservative by reducing the period for completion of the work up dives from 10 days to 5 days. Finally, the types of dives in this series were no-stop or decompression dives to depths greater than 100 fsw, which circumscribes the types of dives that can be considered to count as work up dives.

CONCLUSIONS AND RECOMMENDATIONS

The BDP is ineffective as a means to reduce the magnitudes of PO_2 overshoots that accompany descents in the MK 16 MOD 1 UBA.

NEDU recommends that the BDP be removed from MK 16 MOD 1 standard operating procedures.

NEDU recommends that the following provision be added to MK 16 MOD 1 standard operating procedures to accommodate use of MK 16 MOD 1 $He\text{-}O_2$ Decompression Tables by divers who have not performed work-up dives:

- A diver will be considered "worked up" for a MK 16 MOD 1 dive only if he/she has completed at least two (2) dives to depths greater than 100 fsw in the five (5) days preceding the MK 16 MOD 1 dive. In the absence of information to the contrary, these work up dives can be completed using any U.S. Navy approved diving apparatus and breathing gas.
- A MK 16 MOD 1 diver who is not worked up and is contemplating a MK 16 MOD 1 $He\text{-}O_2$ dive to depth greater than 200 fsw should use the decompression schedule prescribed in the tables for the actual or planned bottom time at the next tabulated dive depth deeper than the actual or planned dive depth. Alternatively, such a diver may use the schedule prescribed for the next tabulated bottom time longer than that normally applicable at the actual or planned dive depth, although the decompression time penalty of this alternative may be unnecessarily high.

Further study may be required if an unacceptable DCS incidence is encountered with use of the MK 16 MOD 1 $He\text{-}O_2$ decompression tables in accord with the recommendation in the previous paragraph. Such studies may motivate more conservative specification of work up dives and the contexts for their applicability than presently recommended.

ACKNOWLEDGEMENTS

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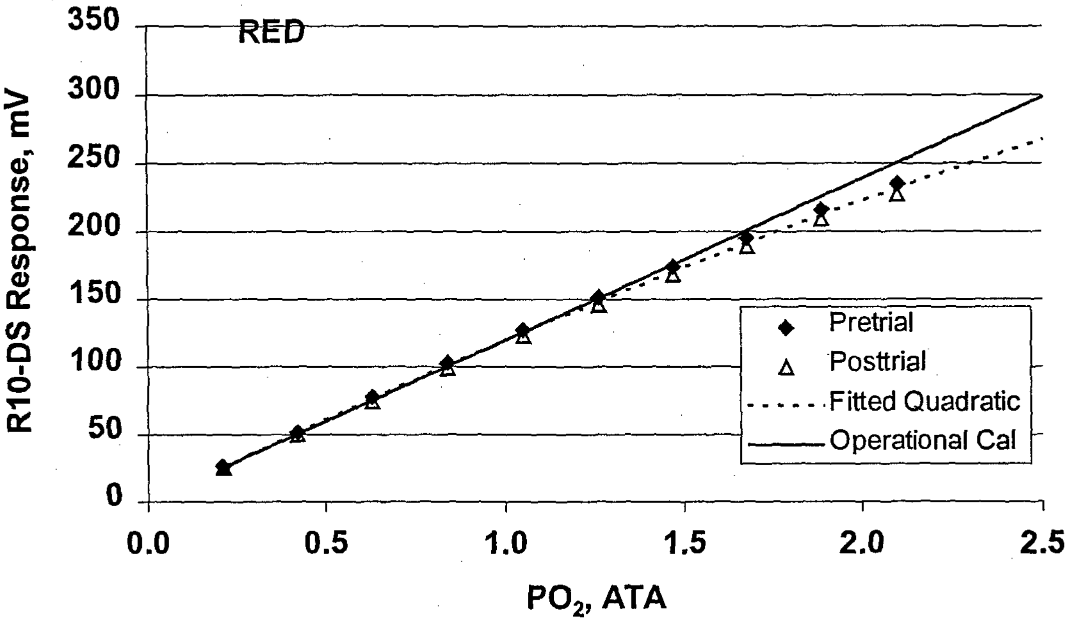
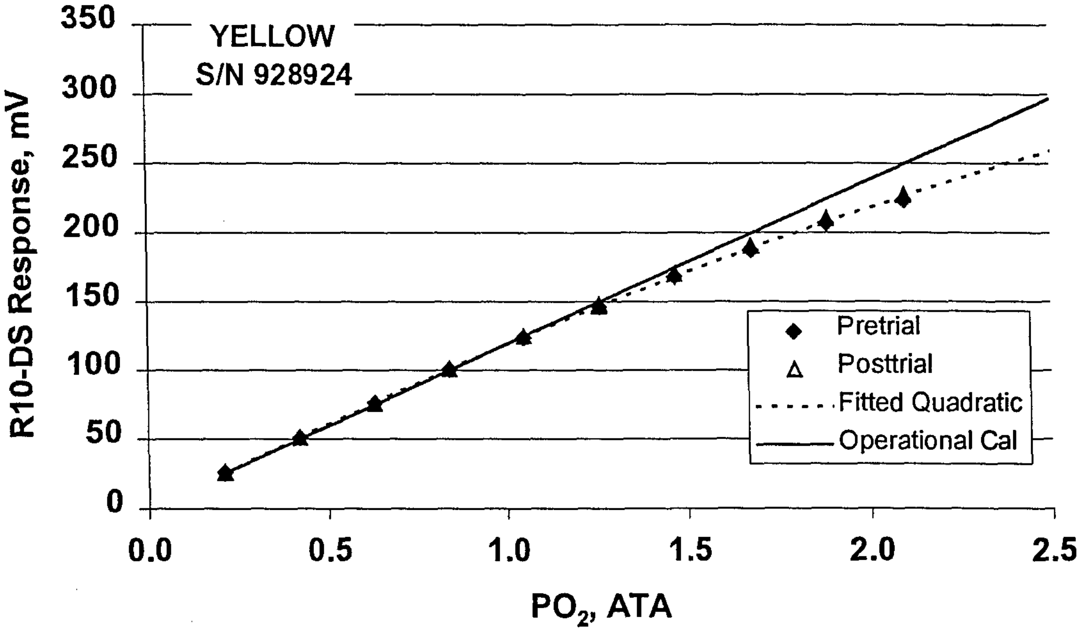
APPENDIX A.

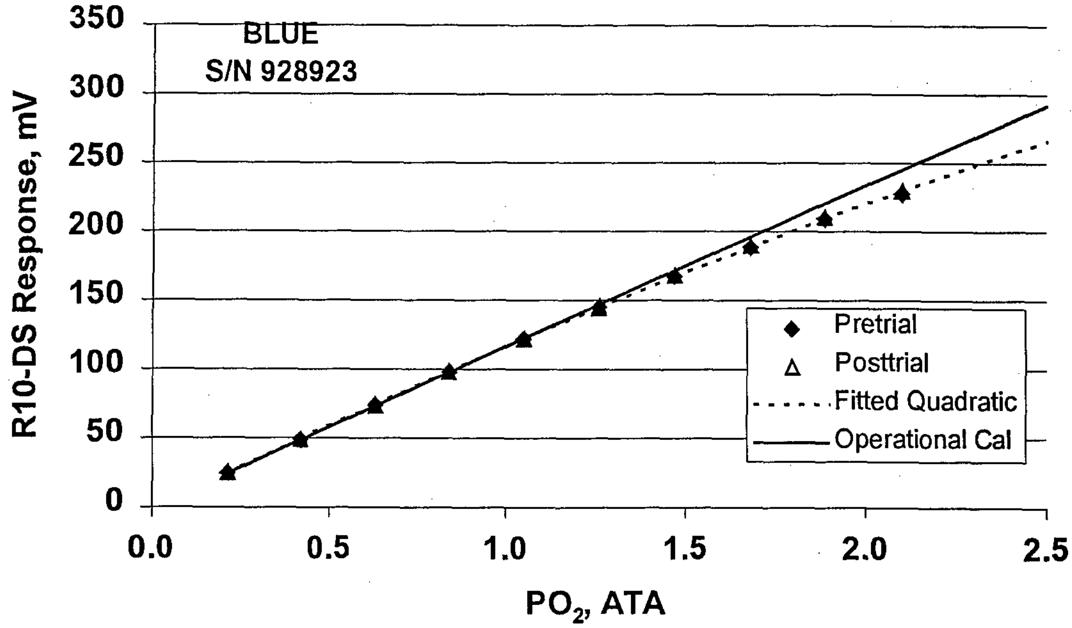
R10-DS OXYGEN FUEL CELL CALIBRATION CURVES



Fitted Quadratic Coefficients (S/N 928926) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	-1.75909
β_1^L	130.21065
β_2^L	-8.99660



Fitted Quadratic Coefficients (S/N 928924) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	-1.95344
β_1^L	131.70995
β_2^L	-10.93015



Fitted Quadratic Coefficients (S/N 928923) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	-1.59136
β_1^L	125.18584
β_2^L	-7.19140

APPENDIX B.

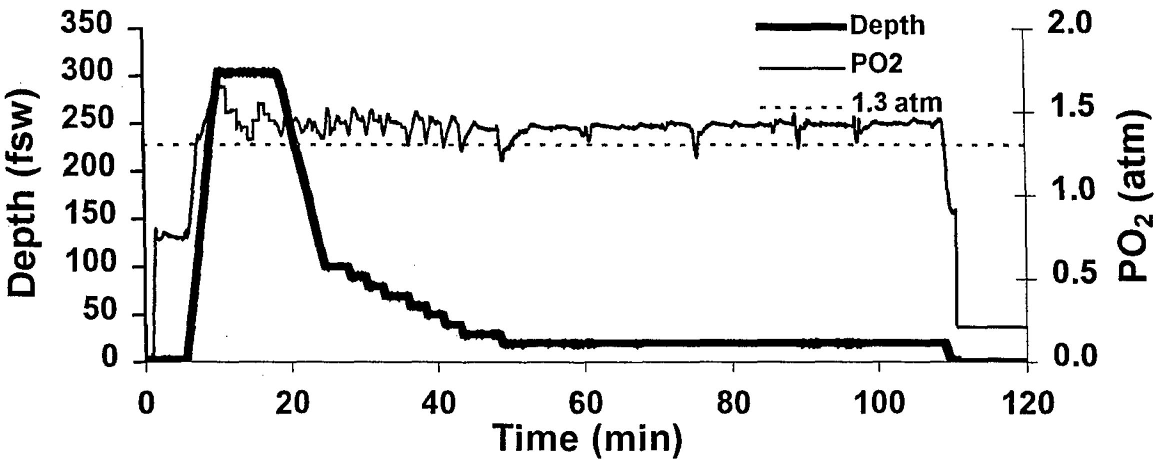
Case Reports for Medical Events

030313YELa
Forty-four-year-old male U.S. Navy diver completed uneventfully a 300-fsw, 9.7-min bottom time dive with $He-O_2$ and the MK 16 MOD 1 in the NEDU OSF, with decompression on the 300/10 schedule from the tables. After emerging from the OSF, the diver took a "hot" shower following elapse of the 10-minute clean time and noticed crampy muscle pain of approximately 2–3/10 severity in the right shoulder, and bilateral superficial shoulder rash. The diver presented to the DMO for examination and was found normal except for a red, marbled rash with purple discoloration on the lateral-posterior aspect of the right shoulder, which was warm to the touch, and a red rash on the left shoulder, which was not warm to the touch. The diver was diagnosed as having *cutis marmorata*, Type I DCS, with decision to treat on USN TT6. The purple discoloration on the right shoulder dissipated, and the associated pain almost fully resolved en route to the treatment chamber, before commencement of treatment 46.5 minutes after surfacing. Right shoulder pain resolved to 0/10, and skin warmth resolved during the first O_2 period of the table. An approximately 1 x 3-inch erythematous area remained on the right lateral deltoid, which was significantly improved from the pretreatment condition. The USN TT6 was completed with full resolution of the erythema and all symptoms.

030313REDb
Fifty-year-old male U.S. Navy diver completed uneventfully a 300-fsw, 9.6-min bottom time dive with $He-O_2$ and the MK 16 MOD 1 in the NEDU OSF, with decompression on the 300/10 schedule from the tables. Approximately 4 hours after surfacing, the diver noticed sharp nonradiating pain, approximately 2/10 severity, at the medial epicondyle of the left elbow. Although the diver had no history of prior injury or pain at this location, he was not convinced that this pain was dive related. The diver self-observed until about 6 hours postdive, when he noted that the pain had moved to the left forearm as a dull ache of 2–3/10 severity, with similar pain in an approximately 1-inch diameter area in the center of the palm of the left hand. The diver reported to the DMO for examination. Neurological examination was normal, and no objective signs were found. The diver was diagnosed with Type I DCS. Persistence of pain motivated treatment on USN TT6, which was commenced 9.1 hr after surfacing. The diver reported transient recurrence of pain (1/10 severity) in the left elbow 2 minutes after the start of the first O_2 period at 60 fsw. All symptoms were then fully resolved after about 8 minutes into the first O_2 period. The USN TT6 was completed, and the diver was released with no recurrence of symptoms.

APPENDIX C.

INDIVIDUAL DIVE DEPTH AND INSPIRED PO_2 PROFILES FOR DIVES PERFORMED



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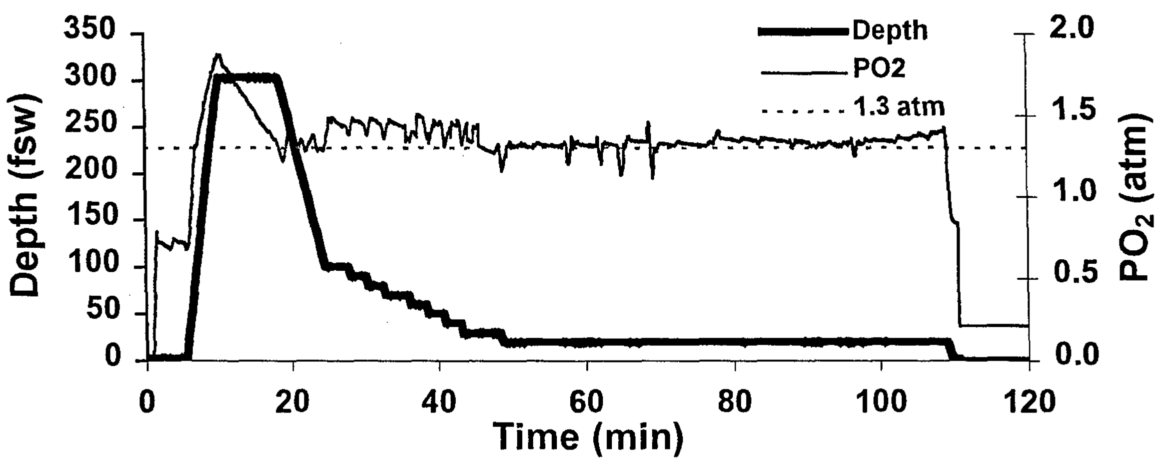

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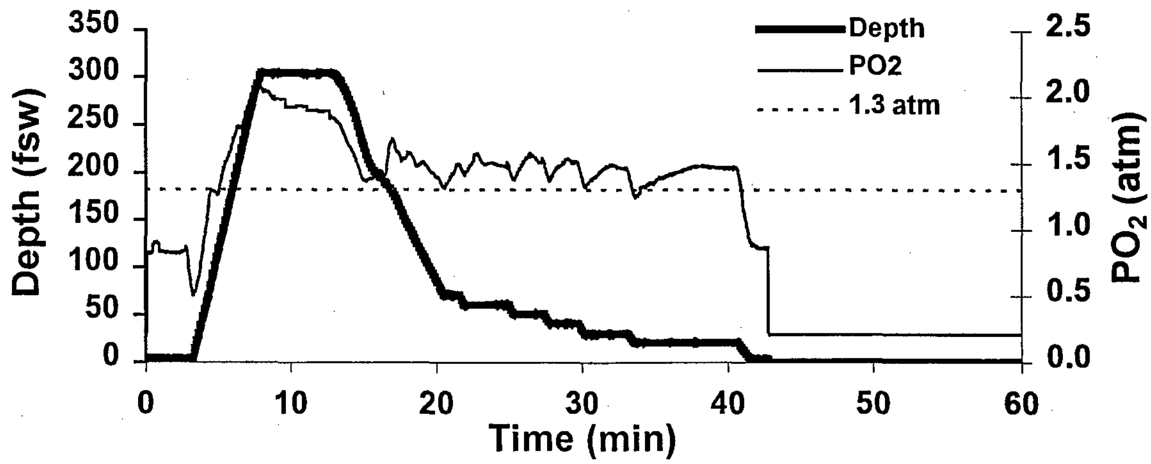

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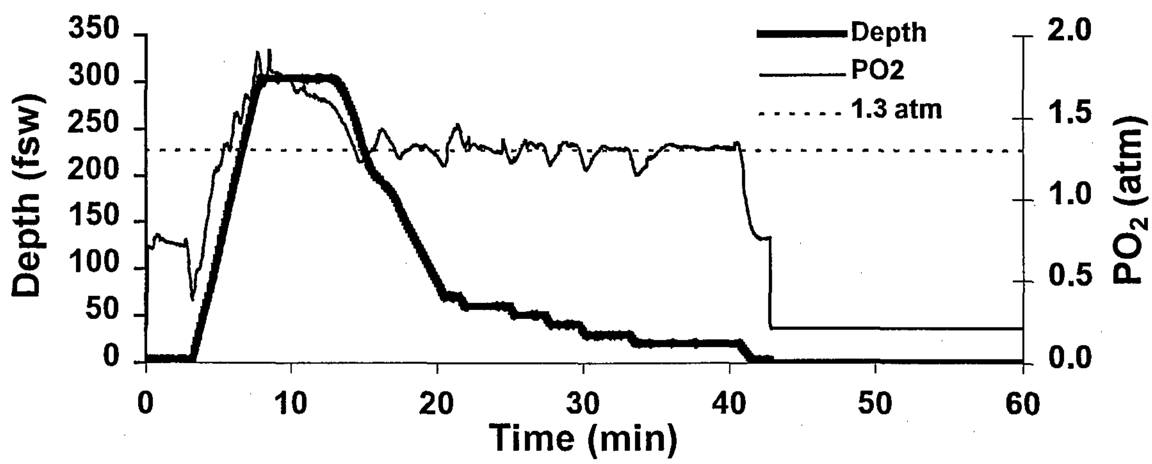

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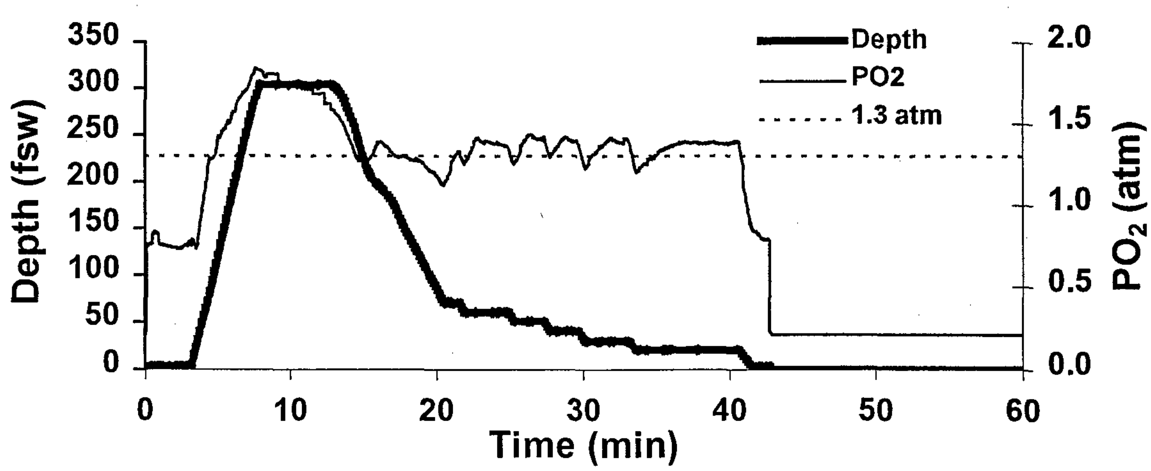

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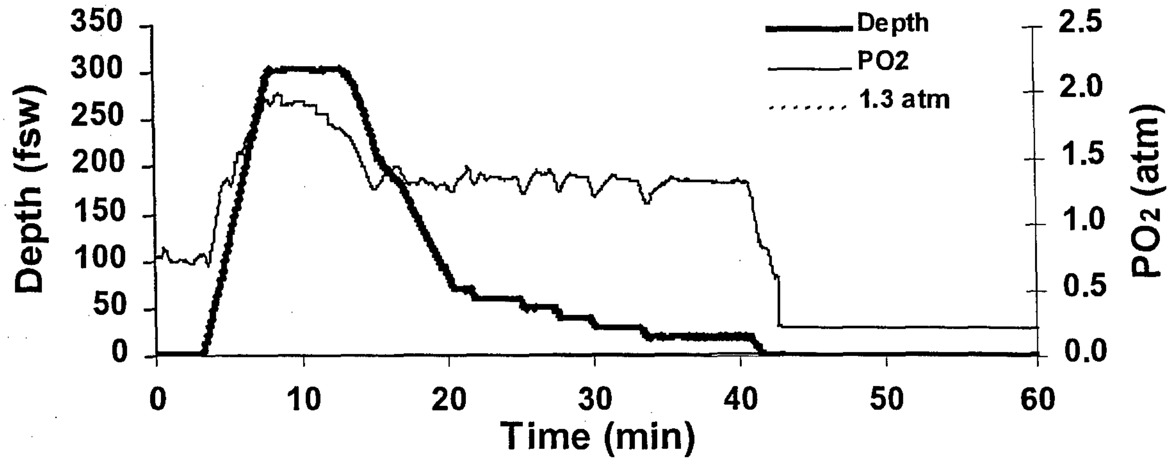

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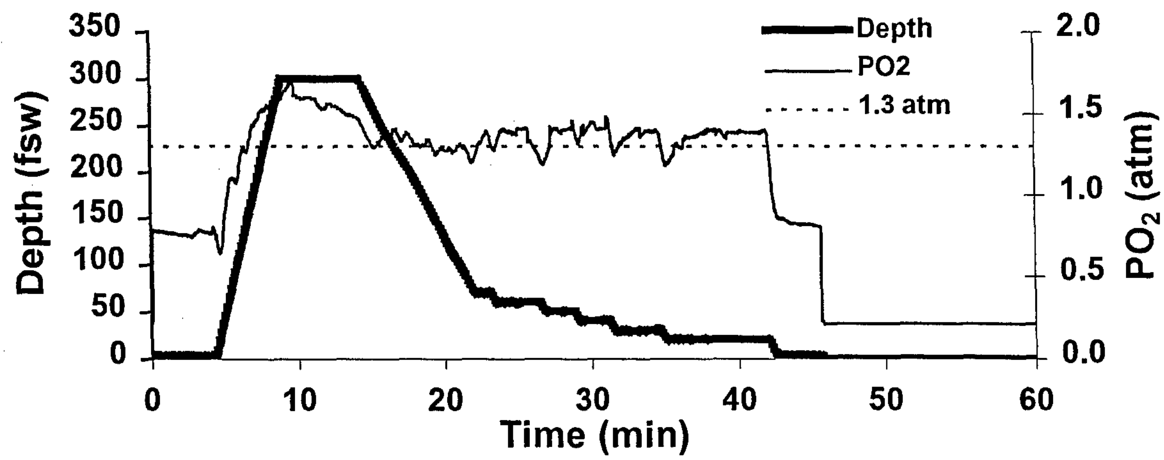

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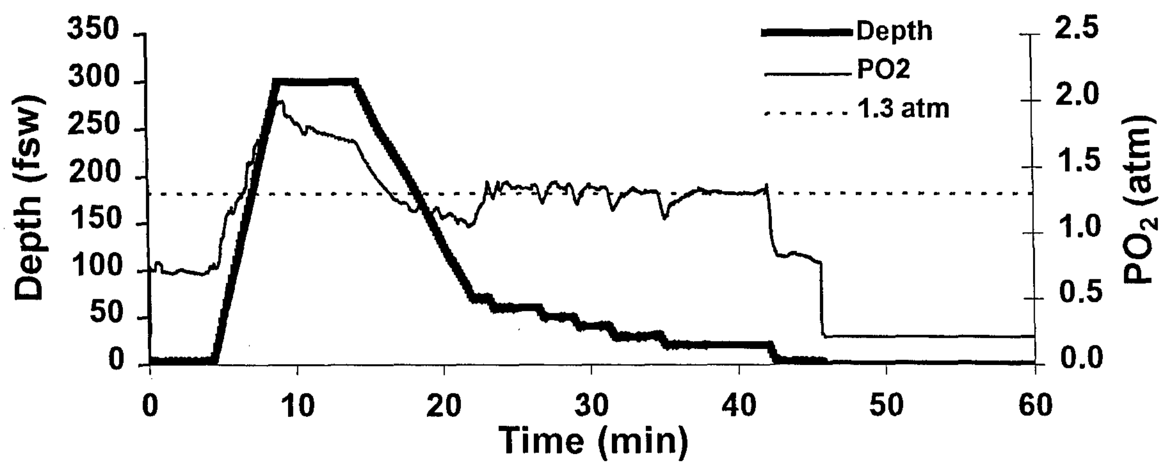

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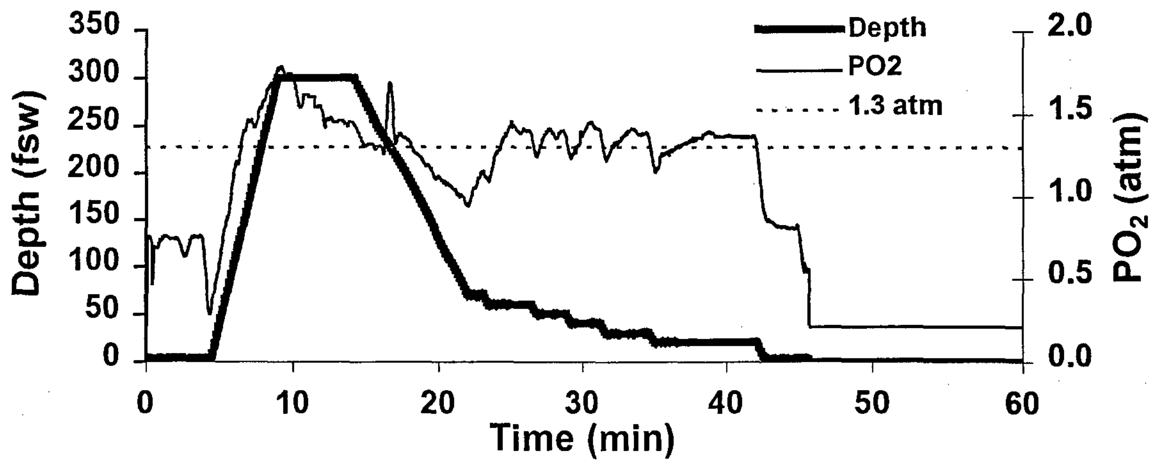

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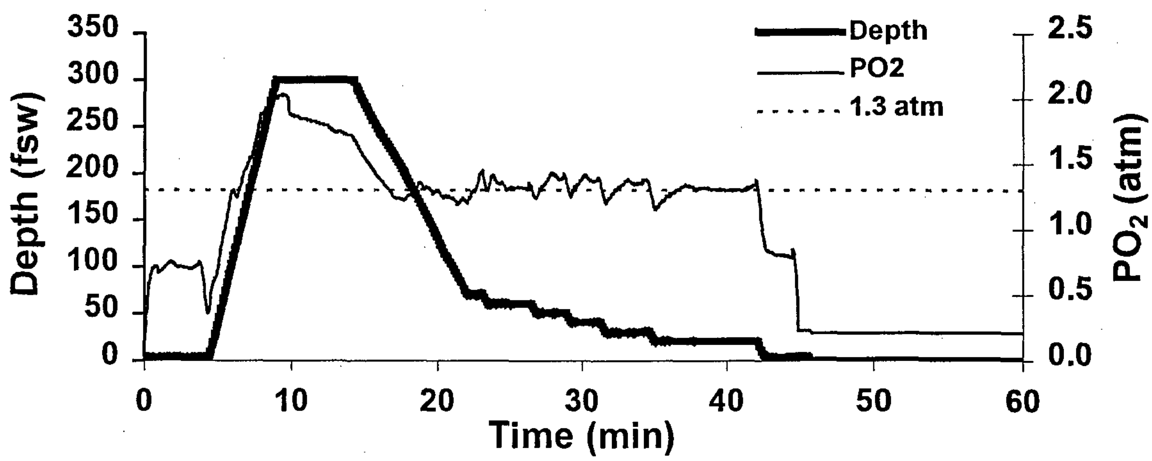

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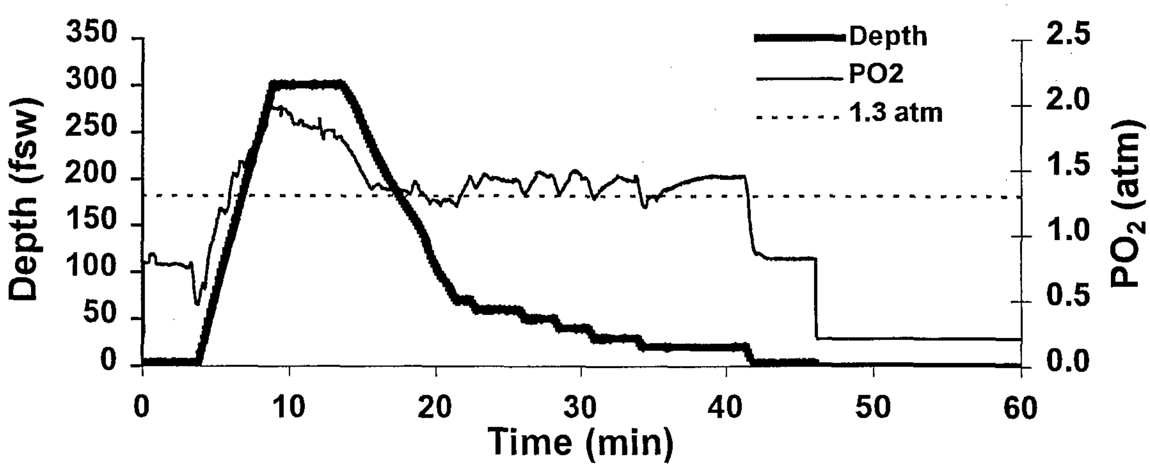

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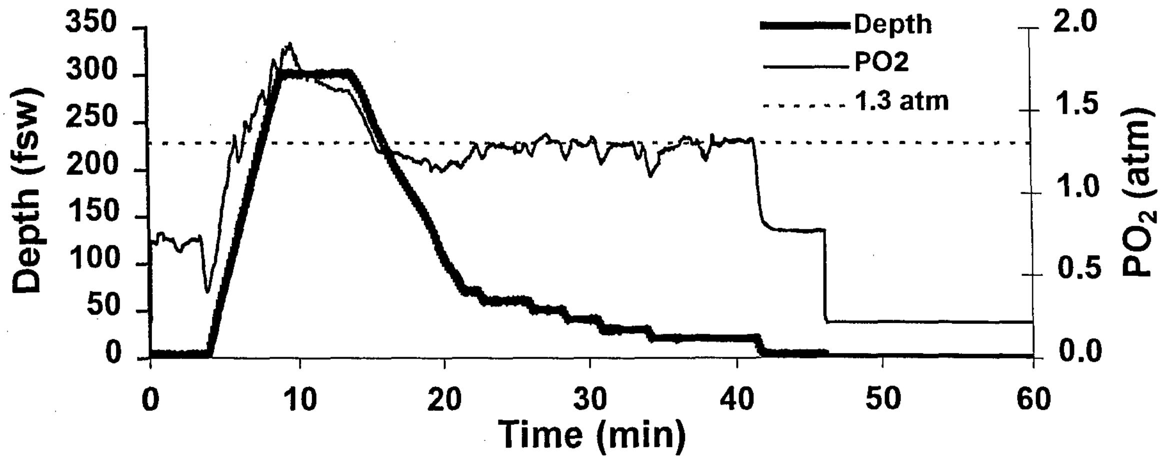

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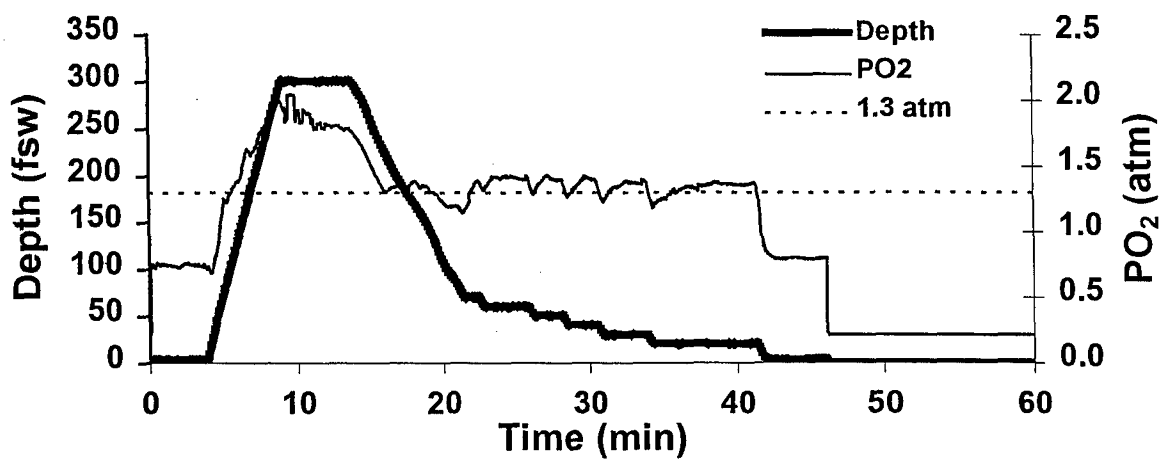

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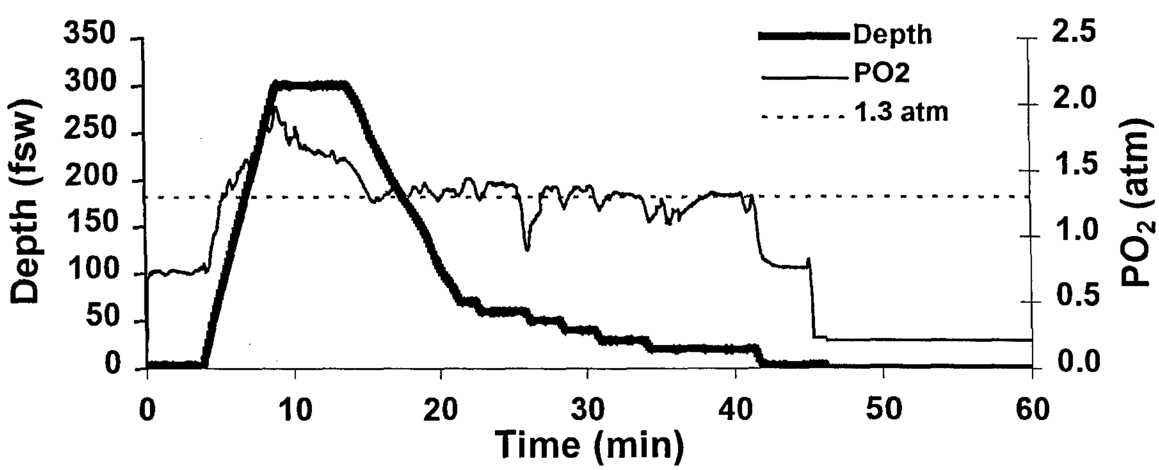

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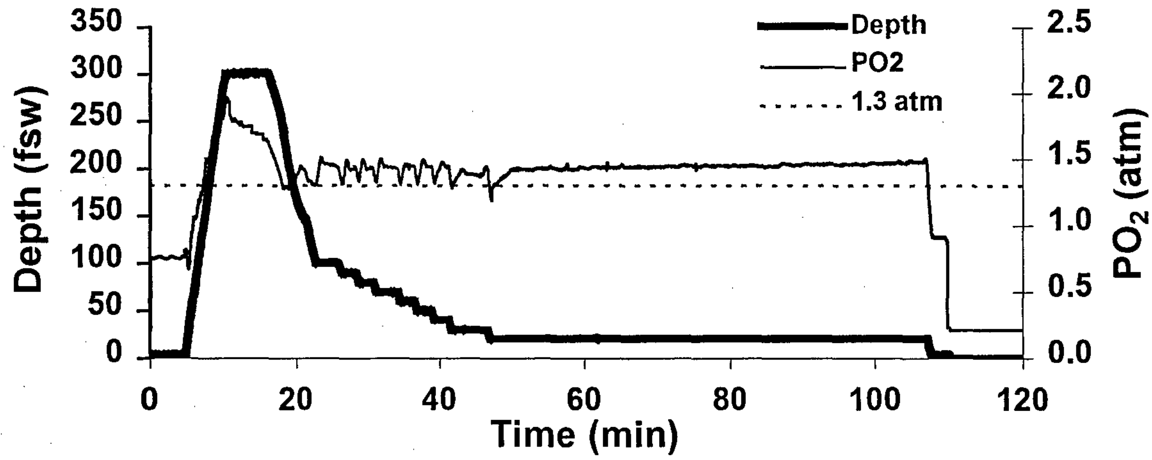

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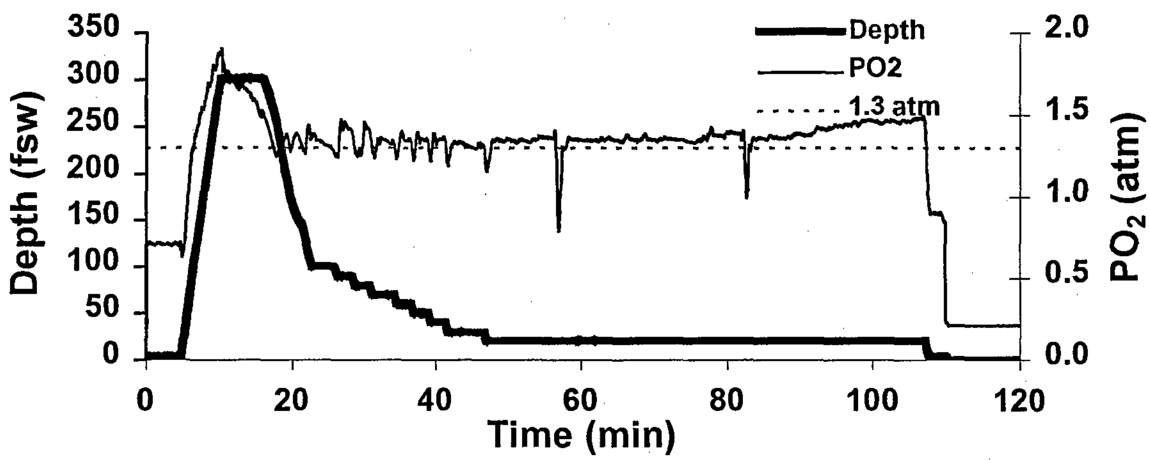

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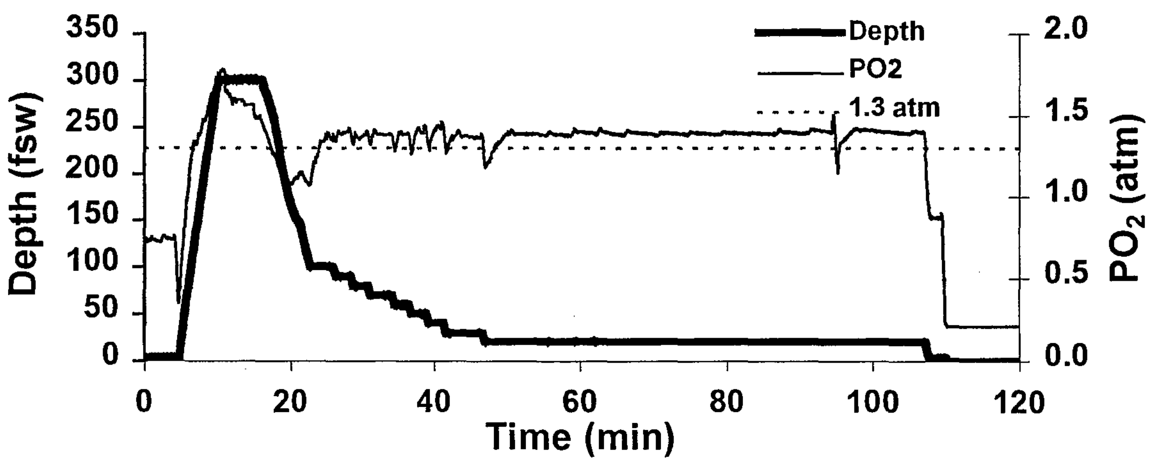

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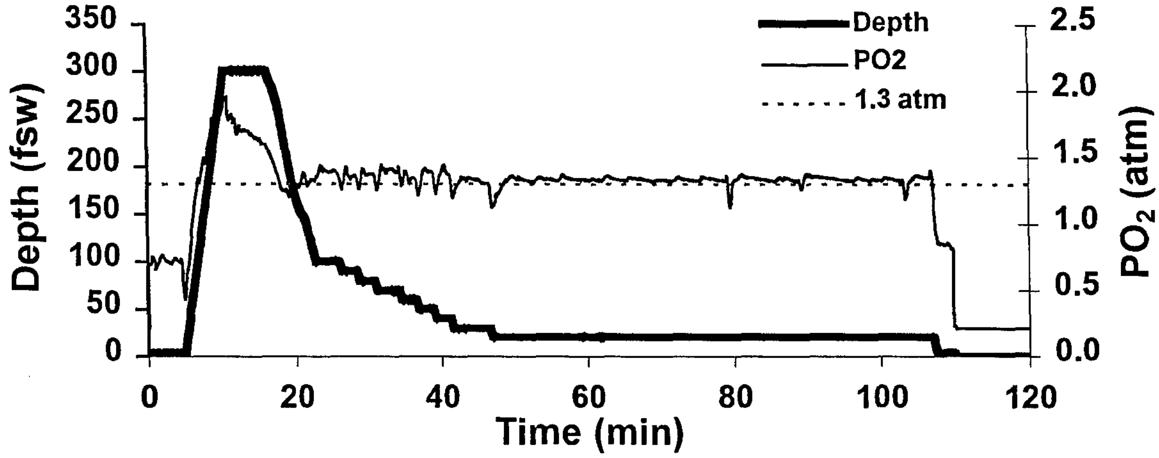

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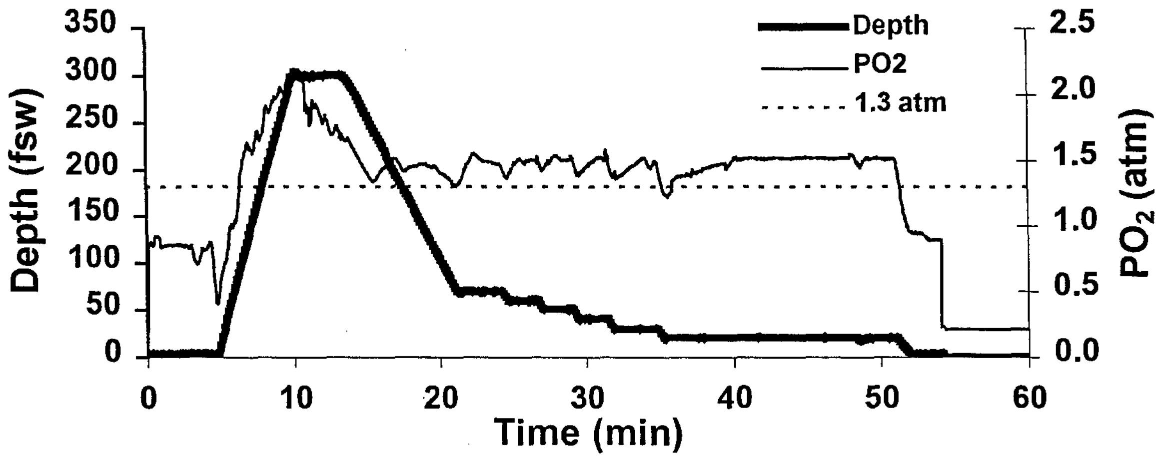

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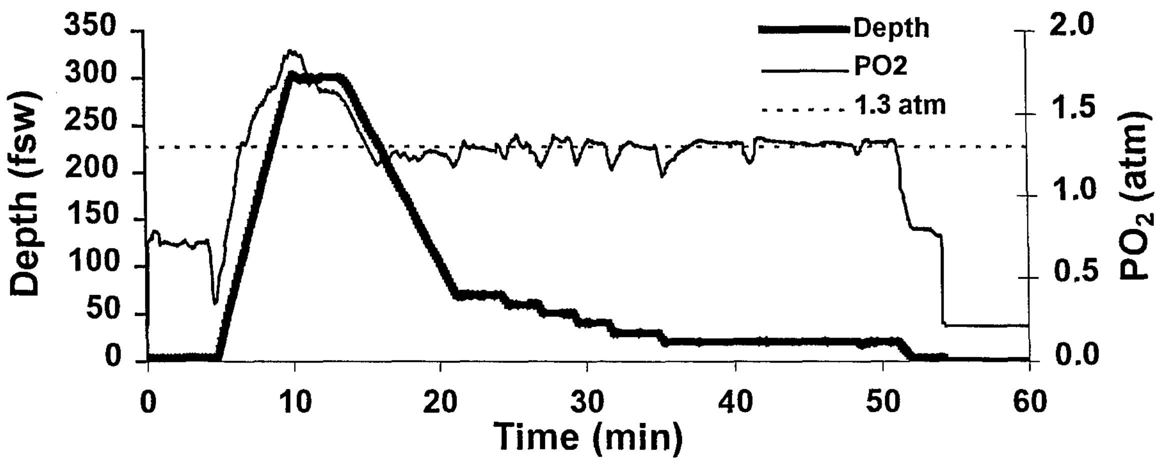

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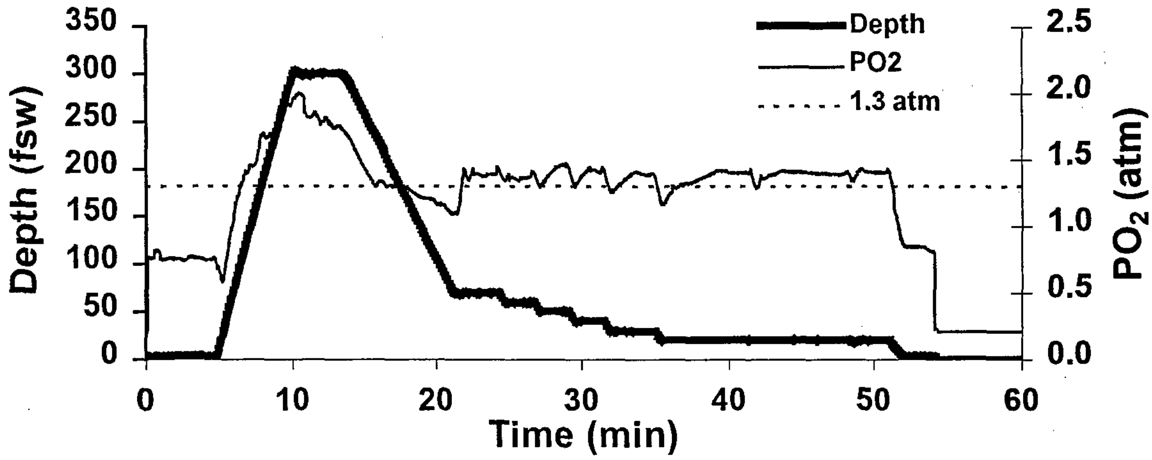

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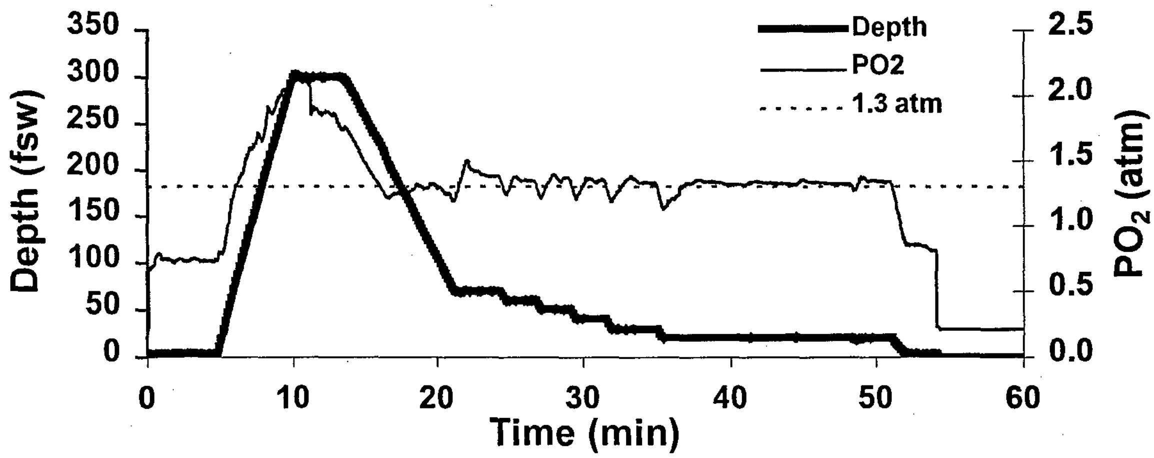

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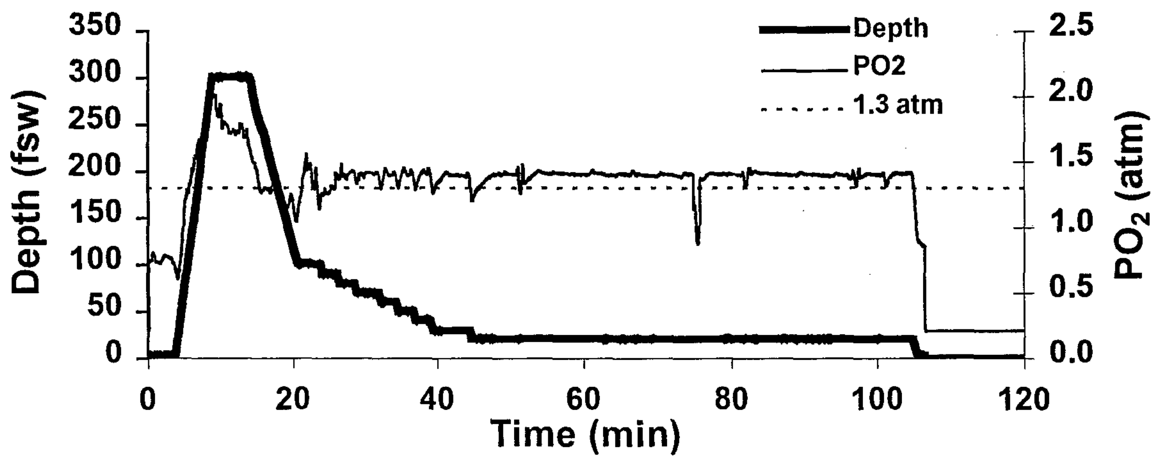

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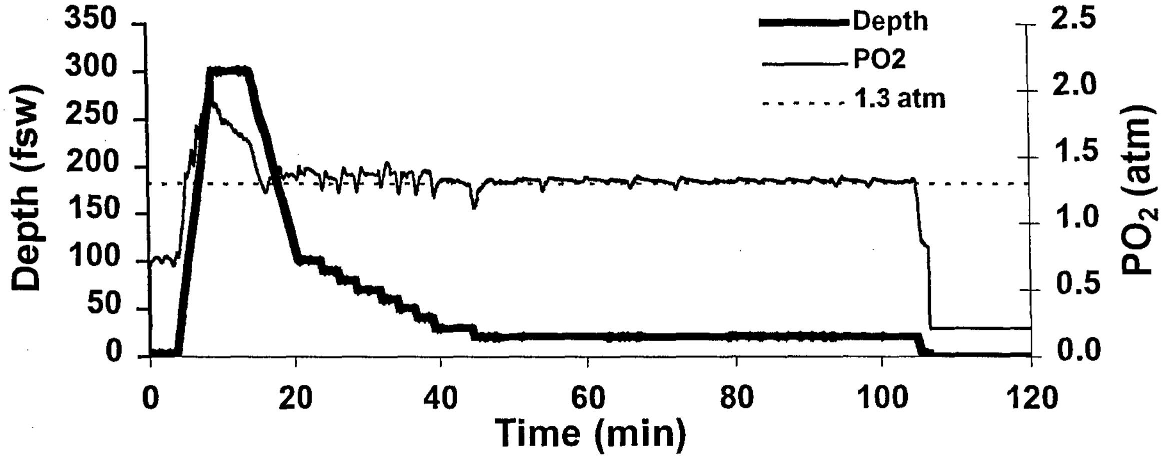

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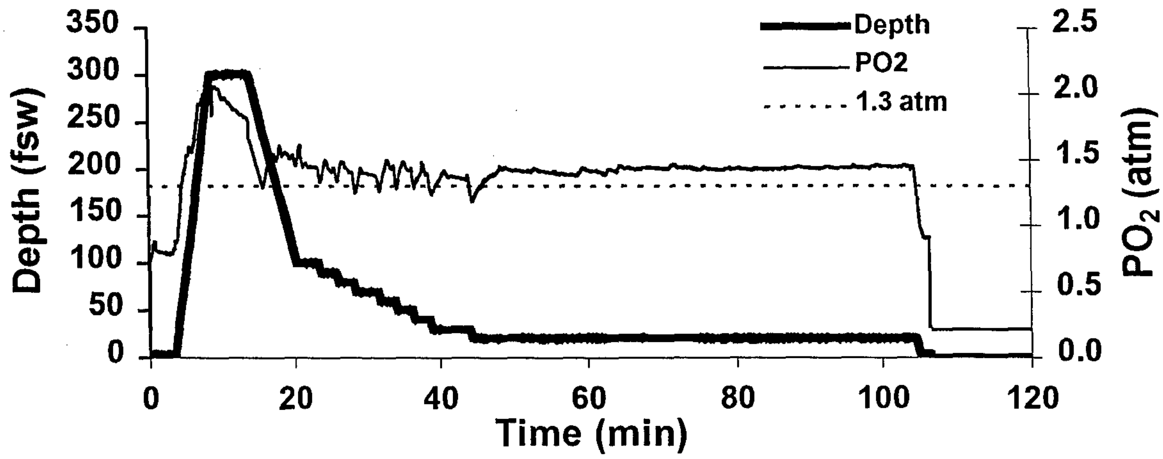

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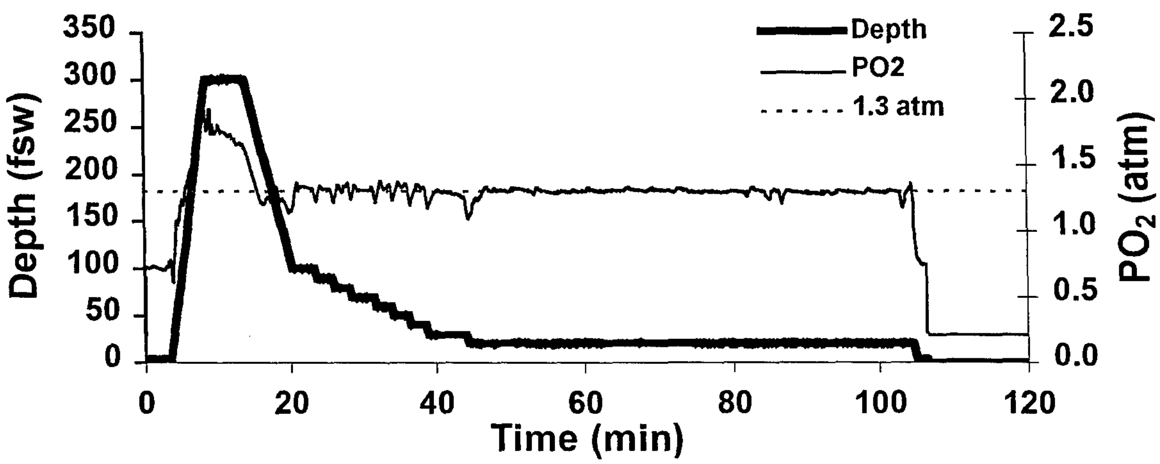

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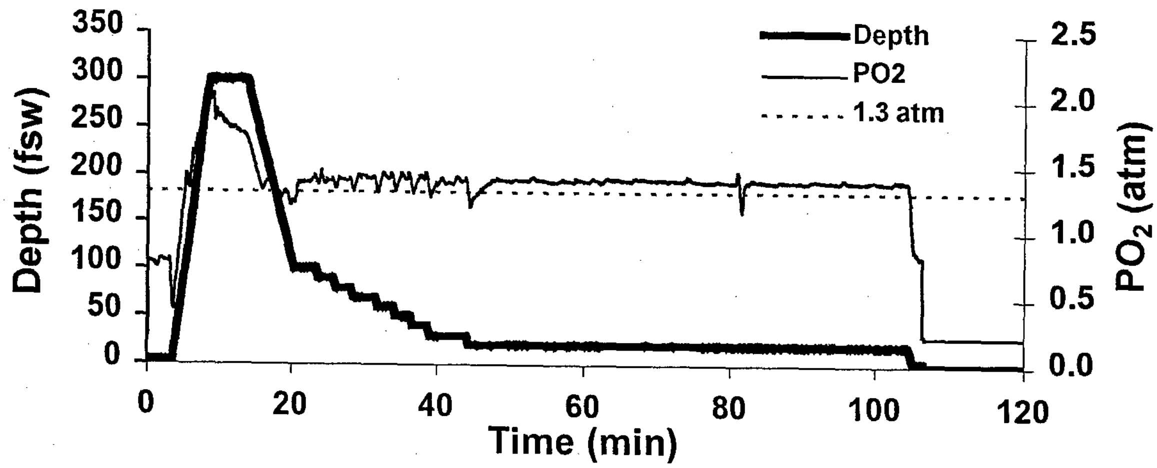

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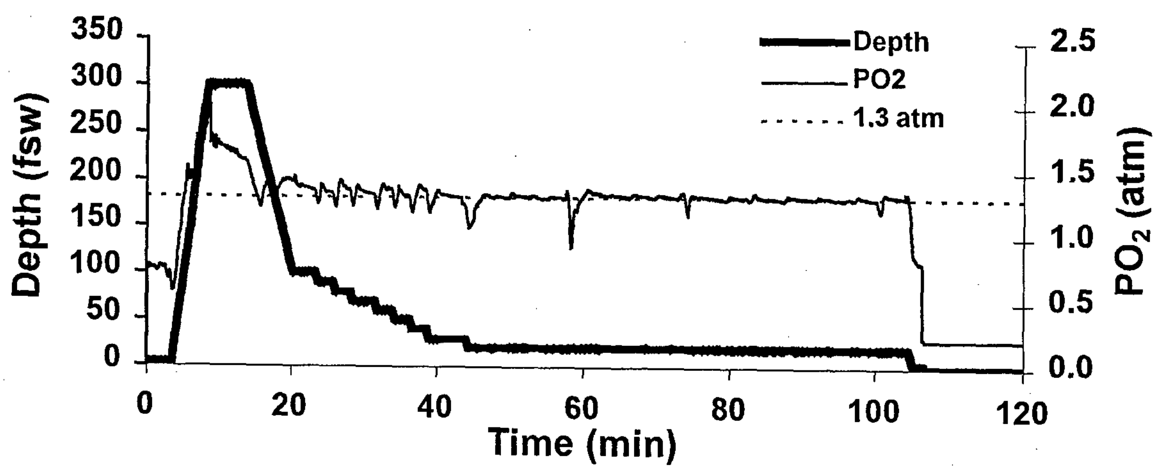

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APPENDIX D.

INDIVIDUAL DIVING INTENSITY DURING PHASES I AND II OF THE MK 16 MOD 1 He-O_2 DECOMPRESSION TABLE DEVELOPMENT AND VALIDATION MAN DIVES

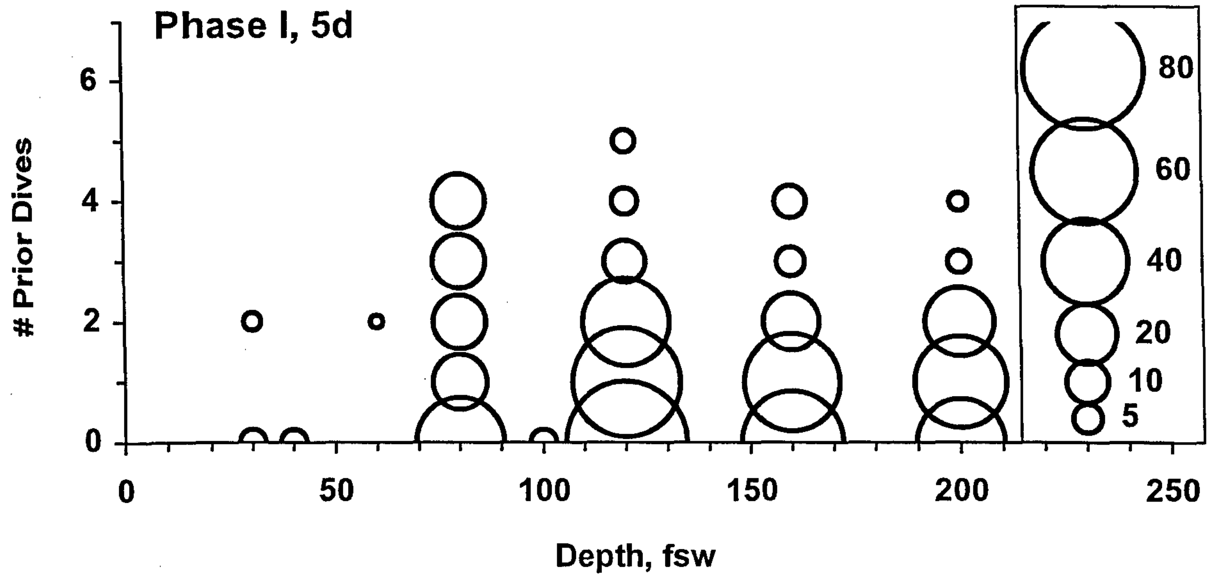

Figure D.1. Number of dives completed by Phase I divers in the 5-day period before a dive to the indicated bottom depth. Circle area is proportional to the number of divers who completed each indicated number of prior dives, as illustrated in the key at right.

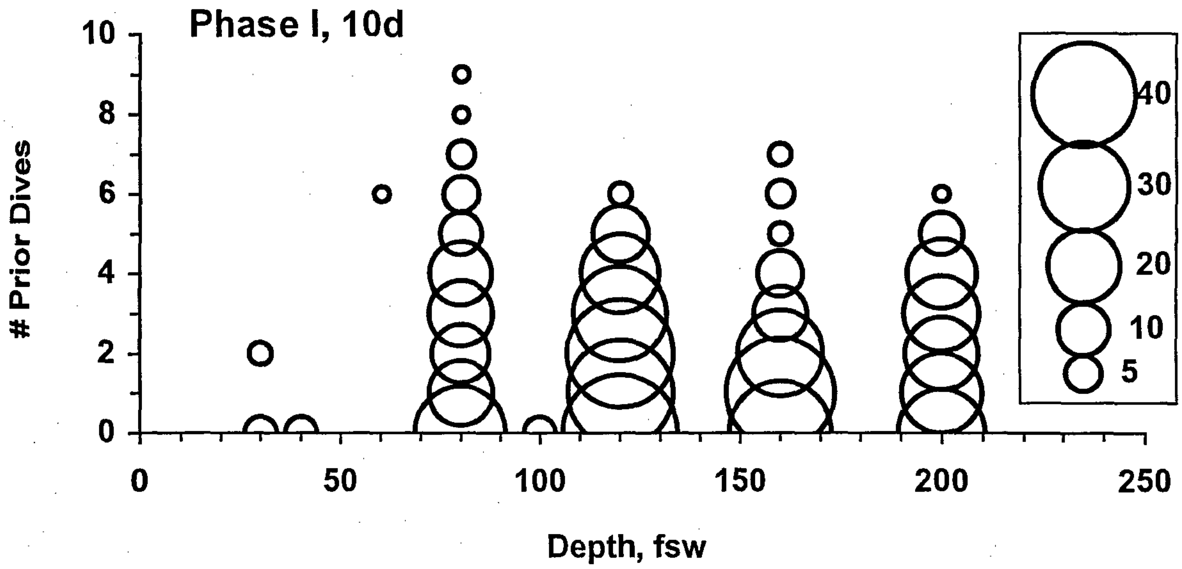

Figure D.2. Number of dives completed by Phase I divers in the 10-day period before a dive to the indicated bottom depth. Circle area is proportional to the number of divers who completed each indicated number of prior dives, as illustrated in the key at right.

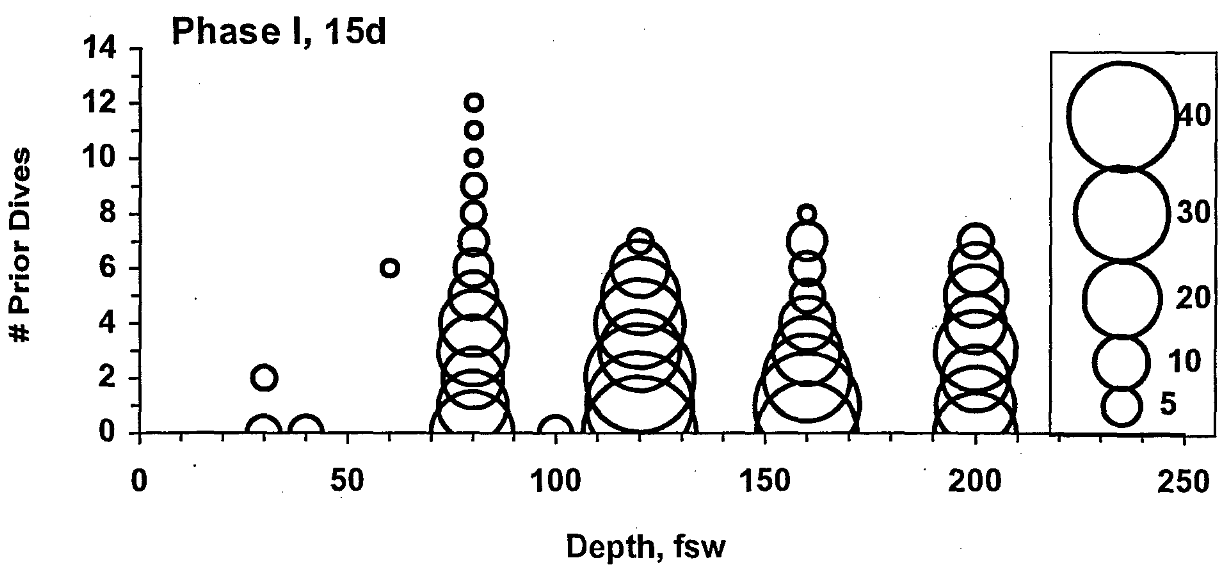

Figure D.3. Number of dives completed by Phase I divers in the 15-day period before a dive to the indicated bottom depth. Circle area is proportional to the number of divers who completed each indicated number of prior dives, as illustrated in the key at right.

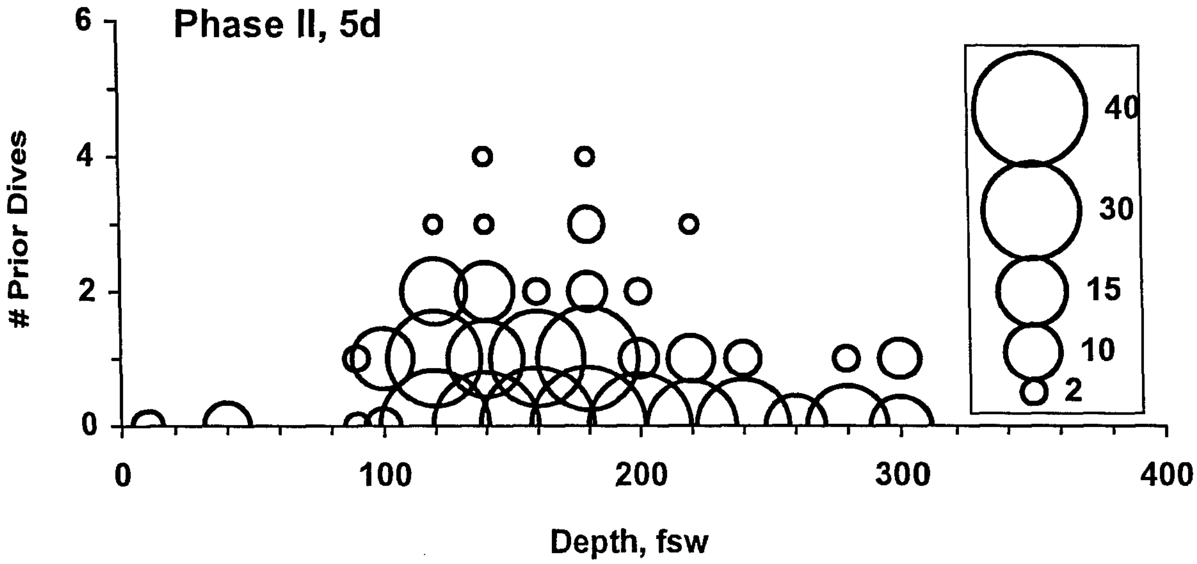

Figure D.4. Number of dives completed by Phase II divers in the 5-day period before a dive to the indicated bottom depth. Circle area is proportional to the number of divers who completed each indicated number of prior dives, as illustrated in the key at right.

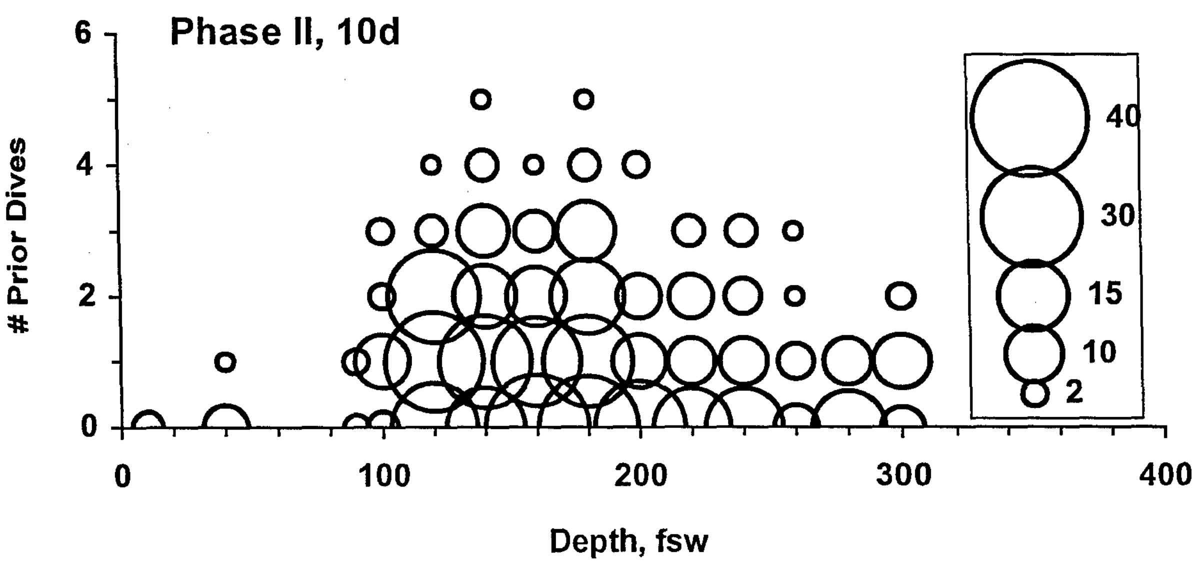

Figure D.5. Number of dives completed by Phase II divers in the 10-day period before a dive to the indicated bottom depth. Circle area is proportional to the number of divers who completed each indicated number of prior dives, as illustrated in the key at right.

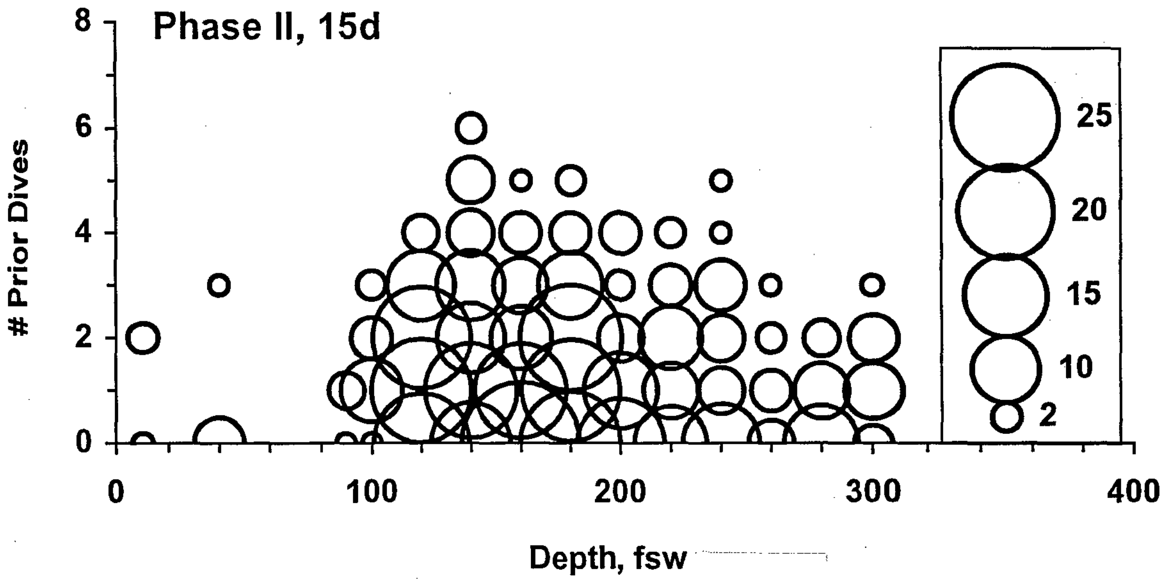

Figure D.6. Number of dives completed by Phase II divers in the 15-day period before a dive to the indicated bottom depth. Circle area is proportional to the number of divers who completed each indicated number of prior dives, as illustrated in the key at right